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# Contributions of Angular Momentum in Gyroscopes to Perception of Heaviness and Controllability

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# **Contributions of Angular Momentum in Gyroscopes to Perception of Heaviness and Controllability**

Thomas R. Brooks, Ph.D.

University of Connecticut, 2018

## **Abstract**

Haptic touch by wielding exploits a number of physical object properties in supporting perception and action. In particular, moments of an object's mass influence judgments of its weight, length, and orientation. In light of this, it has been suggested that these judgments are about something other than the physical dimensions themselves. For example, movability is a quality that depends on task constraints, not just physical properties. Translation and rotation, for example, entail different physical properties to different degrees (inertia and moment of inertia, respectively). While these dependencies hold under a variety of gravitational conditions (e.g., in water or in weightlessness), manipulations of force fields in perception-action tasks requires participants to relearn how to manipulate objects or limbs.

The experiments described here exploit the properties of a classic perceptual novelty—the gyroscope—to explore the role of an altered force field in perceptual judgment and its role in learning. Experiment 1 demonstrates that gyroscopic reactive forces bring about greater heaviness ratings, but only if the reactive force supplements that imposed by gravity. Experiment 2 shows that like heaviness judgments, judgments related to movability change with added gyroscopic spin. However, these effects are not task-specific, suggesting limitations on the relevance of task constraints on perception of object properties. Experiment 3 assessed this in

two domains, namely, the relevance of gyroscopic forces for rotational and translational tasks. Performance worsened with increased spin in the rotational task, but not with the translational task. This result was consistent with gyroscope physics but contrasted somewhat with participant judgment. Experiment 4 examined performance of the rotation task explicitly. Participants performed a tracking task using a gyroscope device, while moment-to-moment perceptual tuning was analyzed. Results indicate that gyroscopic forces impact the perception-action system in a manner more akin to a change in the force field's reference frame than in its overall magnitudes. This means that a gyroscope functions more like a haptic prism than as a means of altering properties at the level of the object.

**Contributions of Angular Momentum in Gyroscopes to Perception of Heaviness and  
Controllability**

Thomas R. Brooks

H.B.A., University of Utah, 2007

A Dissertation

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

at the

University of Connecticut

2018

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2018

## APPROVAL PAGE

Doctor of Philosophy Dissertation

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## **Chapter 1: Introduction**

### **Haptic touch by wielding**

Touch has long been considered special among the sensory modalities. George Berkeley believed that, being a proximal sense, touch was what “grounded” the distal senses such as vision (Atherton, 1990; Berkeley, 1709/2010). While the information that makes vision and hearing possible must cross a medium separating the perceiver from what is being perceived, the perceiver’s body is the medium in touch perception. Berkeley’s claims have received subsequent support in the form of case studies in which patients, born blind or losing their vision early in life, have had their vision restored. While they can identify some object features without touching the objects, most visible object features remain unperceivable to them until they are allowed to touch the objects (Gregory, 2003). The implications of this are still unclear. Does this mean that haptic touch perception is somehow more faithful to object properties, because information has less space to traverse with fewer opportunities to become degraded? Or does it only mean that the development of touch perception advances more quickly in infancy, so as to serve as the basis for the distal senses? In any case, touch perception seems to have a unique place among the sensory modalities which sets it apart from vision and hearing.

Of course, touch perception is supported by several kinds of receptors. The skin contains nerves sensitive to stretching, temperature, and pressure. The joints are sensitive to angle and strain. Nerves in the muscles signal according to their length, strain, and fatigue (Turvey & Fonseca, 2014). These very different types of receptors work together to support a unified experience of body position, movement, and perception of properties of objects that contact the body. Popularly, the senses are distinguished according to anatomical features, with touch being

understood as the sense of the skin, articulators, and tissues. However, the ecological approach categorizes processes of perception, including touch, based on higher-level relationships between the perceiver's intent and surroundings, which lead to measurable differences in the information-gathering process (Michaels & Carello, 1981; Turvey & Carello, 1995). Touch perception is passive, for example, when an object is pressed to the skin. This is a very different process than active touch, in which a perceiver is allowed to feel a surface by palpating, brushing, stroking, or otherwise actively exploring it or using it for a purpose. While both are carried out by many of the same anatomical components, they provide very different experiences and information. Touch perception research historically did not distinguish them (cf. Gibson, 1966), but this has changed in recent decades (Adolph et al., 1997; Lackner, 1981; Michaels & Carello, 1981; Turvey & Carello, 1995; Turvey & Fonseca, 2014).

Additional information is made available by hefting. Wielding an object against gravity, accommodating the object's inertia, provides information about its mass distribution. Sensory mechanisms such as muscle strain and displacement of balance provide exteroceptive information about the object and not just proprioceptive information about the body. Weight, length, width, and shape can be judged this way (see Carello & Turvey, 2015, for a review). However, there is evidence that these physical features are secondary to what is directly perceived. Perceivers accurately judge the action implications of objects and environments while being less successful estimating various putatively more fundamental formal properties (Gibson, 1979/2014). For example, human perceivers judge the climbability of stairs based on the height of the stairs in relation to the perceiver's leg segments despite overestimating the absolute height of wooden blocks (Mark, 1987). Judgment of slant is accurate when reported using a haptic

orientation device compared to verbal report of angle (Proffitt, Creem, & Zosh, 2001). These findings suggest that affordances, not magnitudes, are the objects of perception.

An object's *movableness* appears to underlie judgments of its weight (Shockley, Carello, & Turvey, 2004; Shockley, Grocki, Carello, & Turvey, 2001). Movableness is task-specific. To use an object for hammering requires object rotation (Wagman & Carello, 2001) while sliding an object does not (Carello, Shockley, Harrison, Richardson, & Turvey, 2003). The zeroth, first, and second mass moments of the inertia tensor, are entailed to different degrees by these different task requirements. The symmetry and volume of the inertia ellipsoid—particular geometric configurations of the object's principal moments of inertia—are differentially involved as well.

One of the earliest investigations of perceiving length by touch described how information detected by the haptic system might be understood in terms of forces applied across the perceiver's body. Hoisington (1920) demonstrated that perception of object length is determined to a large degree by the ratio of two opposing forces about the grasped section of a rod held still. As the ratio between “kick” (upward force exerted by the back half of the gripped portion of the handle when the object is held horizontally against gravity) and “pressure” (downward force exerted by the front half of the gripped portion of the object handle) increased, perceived length increased. However, this effect was dissociated somewhat from perceived weight, even though increasing the weight of the object also increases the ratio of kick to pressure, indicating that there is different or at least additional information entailed in weight judgment. Later research indicates that, for static holding of the object, first moment of mass is a better predictor of perceived length than the pressure/kick ratio (Carello, Fitzpatrick, Domaniewicz, Chan, & Turvey, 1992).

Consistent with this, perceivers wielding objects to assess their suitability do so in a way so as to maximize the impact of inertial features on the forces generated through wielding. This leads to stereotypical wielding motions across perceivers for a given task. Participants assessing object length or suitability for reaching a certain distance wield the object through horizontal orientations, where differences in gravity's pull for objects of different lengths is maximum (Harrison, Hajnal, Lopresti-Goodman, Isenhower, & Kinsella-Shaw, 2011). When perceivers are intending to use an object to act, they demonstrate a characteristic repetitiveness (more formally, recurrence) in their exploratory wielding motions compared to when they are instructed to simply wield for a fixed amount of time (Riley, Wagman, Santana, Carello, & Turvey, 2002). This is consistent with a need to gather additional information about an object's action-relevant property.

These findings hold for rigid objects of a range of mass distributions for a variety of tasks. For non-rigid objects, additional object properties can be exploited by a perceiver in making judgments through wielding. When participants grasped springs (directly or by rigid handles) of different lengths, widths, and elasticity, the resulting patterns of tissue deformation allowed perception of length constrained by stiffness as well as inertia (GrandPré & Carello, 2001). Similarly, elastic properties of objects of different material composition structure sound arrays when they are dropped on a hard surface or struck with a mallet, allowing listeners to identify properties of the objects such as shape, geometric dimensions, and material (Carello, Wagman, & Turvey, 2005; Carello, Anderson, & Kunkler-Peck, 1998; Kunkler-Peck & Turvey, 2000). This continuity of energy array structure across media and sensory modalities is consistent with the theory of the global array (Stoffregen & Bardy, 2001), which proposes that specificity is not found in single sensory modalities. Rather, distinct global invariants, defined across energy

media, specify distinct behaviorally-relevant properties. An extended period of active exploration supports extracting these distinct invariants, allowing differentiation of one thing or event from another (e.g., Fitzpatrick, Carello, Schmidt, & Corey, 1994).

In the following experiments, we explore inertial, force-based, and task-specific constraints on haptic perception using a set of gyroscope objects. Gyroscopes are devices whose properties and forces are well formalized in physics and mechanics, but are relatively novel to perceivers. Consequently, they also present an opportunity to begin to examine these issues in the domain of perceptual learning. But research into perception-action effects of gyroscopic forces has so far been limited primarily to their potential for representing events (Badshah, Gupta, Morris, Patel, & Tan, 2012; Murer Maurer, Huber, Aslan, & Tscheligi, 2015) or direction (Winfrey, Gerwitz, Mather, Fiene, & Kuchenbecher, 2009). These experiments aim to revisit and evaluate the family of perceptual theories discussed.

In Experiment 1, we use rod-mounted gyroscopes to explore the combined effects of rotational inertia and gyroscopic forces on judgments of weight. In Experiment 2, we examine whether judgments of gyroscope objects reflect action-relevant properties and whether exploratory motions are carried out so as to maximize detection of these properties. In Experiment 3, we examine whether perceiver judgments are born out in task execution. That is, do gyroscope objects that are deemed less suitable for a task actually lead to worse performance? Finally, in Experiment 4, participants track a square on a screen use a gyroscope object under different conditions of spin rate and added mass. The time series produced in moving the gyroscope object allows an analysis of how participants retune to gyroscopic reactive forces. Together, these experiments provide a basis for understanding how gyroscope objects are perceived in the context of how properties of rigid objects perceived.

## Chapter 2: General Methods

### Terminology

A gyroscope is composed of a mass spinning about a fixed axis. This mass is typically a symmetrical disk that spins about its shortest axis so as to maximize the gyroscopic forces per unit of the assembly's total mass. A flywheel on an axis can be considered a simple gyroscope, though the words *gyroscope* and *flywheel* often denote objects meant for different purposes. A flywheel is commonly an object in engineering whose purpose is to store and dissipate kinetic energy in a controlled manner, and can be composed of a disc, spoked wheel, or individual weights anchored by spokes or cords, while the term gyroscope more often refers to a disk flywheel mounted on one or more gimbals. A flywheel with no gimbals is commonly called a gyroscope when its purpose is not to manage kinetic energy but instead to stabilize an apparatus against gravity or reorientation, or to transduce information about changes in orientation. In this document, the terms are somewhat more interchangeable; a zero-gimbal flywheel will be referred to as gyroscope because its purpose in the following experiments is to generate so-called gyroscopic forces, which occur whenever the angular momentum from a flywheel is redirected, and the term flywheel will occasionally be used to refer specifically to the spinning disk portion of a gyroscopic device. Similarly, the term *force* will be used to refer not only to the strict measure of the concept from physics, but *gyroscopic forces* will refer to gyroscope properties which are present by virtue of the flywheel's spin.

## Physics of the Gyroscope

To reorient a gyroscope to a predetermined angle through a predetermined direction requires a set of forces that is determined by the gyroscope's angular momentum. This spin generates angular momentum ( $L$ ), which is represented as a pseudovector that extends from the spinning mass's center of mass (CM). The direction of the pseudovector is determined by the “right hand rule”, which states that curling one's fingers in the direction of the gyroscope's spin will point the thumb in the direction of the pseudovector. A pseudovector is a quantity with some of the properties of vectors (magnitude and direction), but it behaves differently under transformation in three dimensions. Torque is likewise represented as a pseudovector, and also follows the “right hand rule.”  $L$  is calculated as

$$L = I \times \omega \quad (1.1)$$

Where  $I$  is MOI and  $\omega$  is angular velocity.  $L$  is directional and altering its direction by reorienting its axis requires a torque. However,  $L$  redirects applied torques in an orthogonal direction. These gyroscopic reactionary torques are specified by

$$\tau_{(reaction)} = \omega \times L \quad (1.2)$$

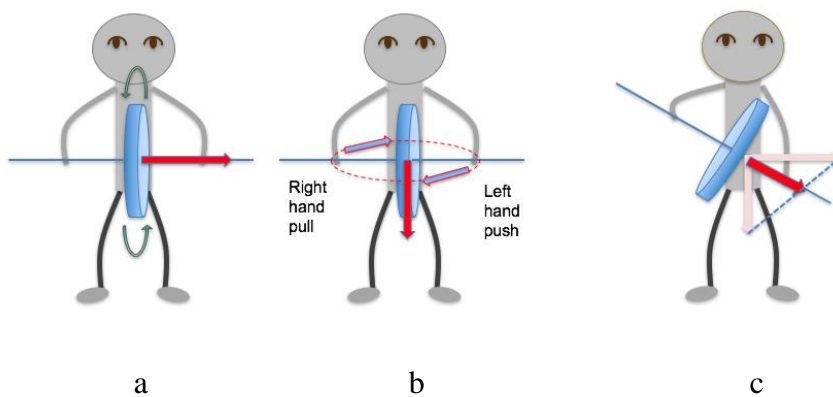
where  $\Omega$  is the angular velocity of the torque. This can also be thought of as the torque required by the wielder to prevent the gyroscope from redirecting torque imposed by the gyroscopic reactive forces.

## Wielding and gyroscopic forces

It is unclear how gyroscopic motion will impact the perceptual system in functional tasks, but there are several things to consider. One is to determine what is meant when it is said that spinning gyroscopes resist rotation. In physics, resistance to rotation is quantified by MOI, but



that measure is only intended to apply to rigid bodies, and not objects with moving parts. For objects with moving parts, separate MOIs are needed for each rigid component. That is, there would be one MOI for the flywheel and one for everything else, including the motor and axle. This is the framework around which previous research on perception of inertia object properties was conducted, and it is not clear from those experiments what the effect will be of angular momentum ( $L$ ) on perception of object properties. For a naïve wielder, reorienting a spinning gyroscope to a desired orientation requires supplying a torque of the quantity and in the same direction that would be required if it were not spinning, plus an additional torque that is equal and opposite to the gyroscope's reactionary torque (Figure 2.1). Therefore, we might expect, naïve wielders to experience the gyroscope as being more resistant to rotation when it is spinning than when isn't, but this is not strictly true. This apparent resistance is an artifact of the redirection of torques supplied by the wielder.



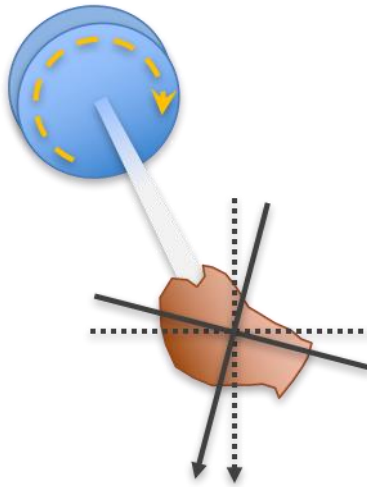
*Figure 2.1.* (a) When the gyroscope “top-spins” in the frontal plane,  $L$  (angular momentum) is in the direction of the holder’s left hand. (b) If the holder attempts to twist (apply a torque to) the axis of the gyroscope in the transverse plane,  $L$  is generated in the direction of the ground. (c) The reactionary torque produced is a product of the two contributing pseudovectors. The axis is now tilted diagonally, contrary to the wielder’s intention.

Experientially, there are two different ways in which a spinning gyroscope can be said to resist rotation. First,  $L$  follows Newton's first law in that it tends to continue in its same direction. The greater the  $L$ , the more it resists this change. However, this resistance is qualitatively different from that of moment of inertia (MOI). A higher MOI means that while it requires more torque to start an object rotating, it also requires more torque to stop it from rotating.  $L$ , by contrast, tends to continue to point in its current direction. This means that while it is harder to start reorienting a gyroscope's axis while it is spinning, it is paradoxically easier to *stop* its reorientation. At any given moment during the rotation,  $L$  wants to point where it currently points. This can be thought of as a sort of damping effect<sup>1</sup> on rotational movement. A familiar example is bicycle riding. The spinning bicycle wheels resist reorientation, and even when the wheels are torqued by the rider so as to reorient (such as in a making a turn), they continue resisting rotation. For wielding, this suggests that an increase  $L$  could be interpreted as increased weight, since it is harder to initiate rotation in heavier objects due to the supplied force is being redirected. At the same time, it can seem easier to slow the rotation of a gyroscope's axis when it is spinning, since the wielder is likely already applying a corrective torque in a direction contrary to the gyroscope's reactive torque. Therefore, a gyroscope's movability, like that of other objects, is likely to be determined by task. Tasks that require a fast initiation of rotation but are less dependent on precise slowing of rotation would likely be more difficult with added  $L$  while a task with the opposite requirements would potentially be easier.

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<sup>1</sup> "Damping" only serves as a qualitative description of the effect. While angular momentum superficially appears to behave as damping for a brief impulse or collision of an object with part of the gyroscope's axis, torques are redirected rather than absorbed as they would be by a true damping effect such as friction.

The second way that spinning gyroscopes could be said to resist rotation is their redirection of torques in a perpendicular direction, as explained in the previous section. For wielding, this means that the force field required to change the gyroscope's axis from one specific orientation to another is directionally shifted.  $L$  redirects torques that are perpendicular to its axis in the direction that is perpendicular to both the direction of the torque (its pseudovector) and  $L$ 's axis. The amount of torque that gets redirected depends on the magnitude of  $L$  (equation 2). While this does not necessarily affect the absolute magnitude of the impulses (torque applied over a period of time) required to start-then-stop an object's rotation, it could well affect the perceived difficulty of rotating an object through a desired trajectory, since the object responds in a counterintuitive manner. What this amounts to for the participant is a warping of the force field required to wield a spinning gyroscope in a particular direction, compared to if it were not spinning (Figure 2.2).



*Figure 2.2.* The force field required for holding and wielding a rod-mounted gyroscope when the gyroscope is spinning (solid line) and when it is not (dashed line).

Previous work in changing the force field for wielding is informative for comparison. Shadmehr and Mussa-Ivaldi (1994) used a 2-dimensional reaching task in which a manipulated object was attached to an actuated robotic arm. The actuators in the arm were used to impose an altered viscosity profile onto the task workspace. Their results showed that participants adapted to the altered force field in a manner similar to recalibration in prism adaptation. That is, a gradual learning curve returning performance to the levels of the previous condition was seen when the force field was introduced, and an aftereffect was apparent when the viscosity profile was removed. Additionally, participants demonstrated transfer effects when the task was expanded to other workspace regions. Note this experiment involved translation of a handle, but that for gyroscopes, translation alone does not invoke gyroscopic reactive torques.

Other research on perceptual transformations is equivocal about what the consequences of added  $L$  might be for tools. For example, forces that arise from the Coriolis effect cause deviations in reaching trajectories that followed pre- and post-test adaptation curves (Lackner & DiZio, 1994), similar to those seen in prism adaptation. It was shown that when a room was rotated below the perceptible level, Coriolis forces changed the reaching trajectories of participants to follow a curvilinear path instead of a straight one. Gradually, participants corrected the trajectories through repeated trials. However, when rotation ceased, participants reached in a curvilinear trajectory towards the opposite side as during rotation, eventually correcting over multiple trials. A similar effect (curvilinear trajectory with learning curve) was seen in a follow-up study (Cohn, DiZio, & Lackner, 2000) when illusory rotation was imposed upon participants, but there was no aftereffect when the illusion was removed. The authors suggest that this is because aftereffects are caused by alterations to different components of participants' motor plan depending on whether they have explicit knowledge of the presence of

Coriolis forces. When they do have explicit knowledge, this additional feature of their motor plan can essentially be switched off by the executive system. However, in prism adaptation studies, participants have explicit knowledge of wearing prism glasses and are aware of what transformations have taken place, yet they experience latent aftereffects when the prisms are removed. An explanation for Lackner and DiZio's results that squares with prism research might be that vision is grounded in touch after all, or more precisely, in action. When only the visual background is transformed, and that transformation does not bear on task, participants need not attend to it. This is different than in the tasks which imposed Coriolis forces, since those forces actually change the force field for the task. In prism experiments, the force field for wielding tasks is unchanged, but the transformation of both background and egocentric workspace (in other words, the information which specifies the task's force field) are transformed together.

In light of this, it is unclear whether changing the force field about a local axis (as is the case with a wielded gyroscope) would similarly lead to aftereffects in wielding. On one hand, the transformation imposed by gyroscopes is task-relevant because it bears on the forces required to guide the gyroscope through rotation. On the other hand, if participants are using a mental model in which the torques they impose with their hands are mentally recalculated to adjust for the gyroscopic effect, they ought to be able to "switch off" this adjustment almost immediately when it is absent. One way to determine this is to create conditions in which participants must rotate a gyroscope's axis through a particular trajectory in order to execute a task. An initial period of completing the task with the gyroscope off, followed immediately by a period with the gyroscope spinning, and then a final period with the gyroscope off again, would demonstrate whether adjustment to and away from gyroscopic force fields is better understood as a process of inclusion and exclusion of a mental model component, or as a perceptual tuning process.

To test the influence of angular momentum ( $L$ ) on weight perception requires manipulating  $L$  without adding too much extra mass, which could suppress the contributions of  $L$ . Therefore, a large proportion of the mass of the wielded gyroscope object should be contributed by the flywheel, allowing a large change in  $L$  with no change in mass. Additionally, to experience different magnitudes of  $L$  under different weight conditions also requires that the unweighted object must be relatively lightweight so as to provide a range of heavier objects that will be possible for participants with a range of abilities to lift comfortably. In other words, what is required is a large degree of  $L$  without a large degree of mass.

One way to get this is to use a high very high angular velocity (Equation 1.1). However, spinning a motor faster to produce a higher angular velocity can increase vibrations. Therefore, for these experiments, we selected a brushless DC motor to provide spin to the gyroscope device at a high angular velocity and with minimal vibration. We sourced Hard Drive Disk (HDD) motors from surplus computers to construct the gyroscope objects. Such motors have been used by other researchers to create high velocity control moment gyroscopes (Murer, Mauer, Huber, Aslan, & Tscheligi, 2015; Badshah, Gupta, Morris, Patel, & Tan, 2012).

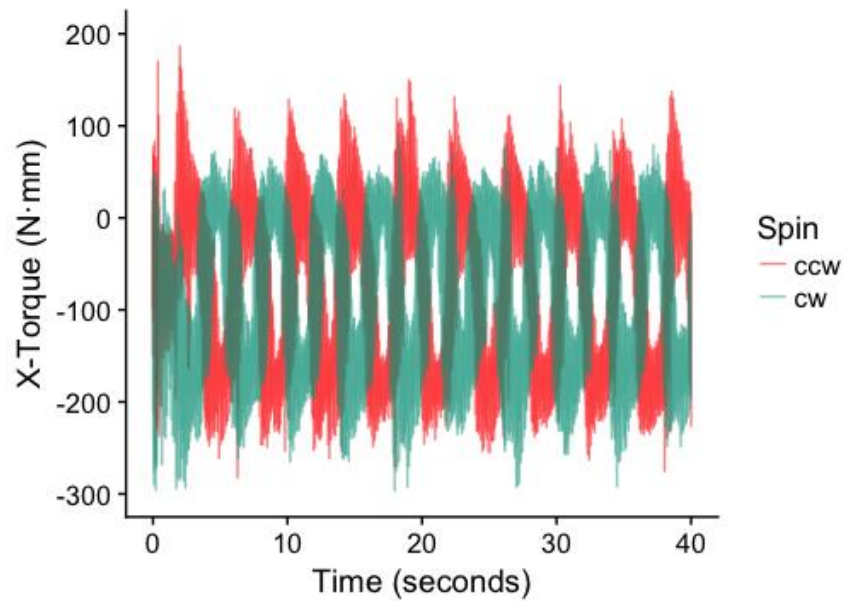
The length of handles selected determines the degree to which gyroscopic forces are brought to bear on touch perception. The axis of rotation for wielding is about the wrist, and that is where MOI's influence has typically been assessed (Pagano, Carello, & Turvey, 1996). For a palm width of 8 cm, a mass of 50 g will exert 250 g of “kick” at the base of the pinky and 250 g of “pressure” at the base of the thumb when attached to a shaft of 20 cm, and 500 g each of kick and pressure when mounted at 40 cm. (This is in addition to the 50 g of force supplied by the wielder's arm to support the object against gravity.) Conversely, mounting a gyroscope on a longer shaft reduces the torque about the wrist imposed by the gyroscope's reactionary forces.

## Testing

As a preliminary test, two HDD platters, each weighing 30 g, were attached to an HDD motor to serve as the gyroscope assembly. The assembly was mounted onto a 40 cm aluminum rod such that the axis of spin was along the length of the rod. The rod was mounted onto a Force/Torque sensor (ATI Mini45 Titanium model) using a custom made presswood plate, which was mounted onto a steel hinge joint. The motor was powered and regulated by an off-the-shelf HDD motor driver integrated circuit board. Wires were fed through the hollow rod and the center of the torque sensor. A hinge joint was situated so as to move the rod in a horizontal arc similar to a human wielding a rod through the transverse plane. The axis of the hinge joint was located approximately 3 cm behind the torque sensor.

A human controller rotated the hinge joint back and forth through an arc of 180 degrees at a rate of one full oscillation every two seconds. Timing was indicated to the human controller using a metronome set to 120 beats per minute. Ten consecutive oscillations were performed each trial. Ten trials were performed with the gyroscope spinning at 733 rad/s clockwise and 733 rad/s.

Expected torque differences were calculated as follows. The angular momentum produced by the disc of 60 g with a radius of 4.5 cm spinning at 733 rad/s is  $48.5 \text{ gm}^2/\text{s}$ . From this, we can determine the degree to which the torques imposed on the gyroscope were redirected from the wielding (y) axis to the horizontal (x) axis. A reorientation of  $180^\circ$  ( $\pi$  radians) over 2 s will produce an average torque of  $76.145 \text{ N}\cdot\text{mm}$ , which varies with the rate of rotation over the course of the swing. Figure 2.3 shows the changing torque profile for the two spin directions (clockwise and counterclockwise) across 10 reorientations of the gyroscope device's axis of  $180^\circ$ .



*Figure 2.3.* Torque as a function of time and spin direction.

As expected, the directions of the gyroscope device's reactive forces are anisotropic for welding. In one welding direction, a counterclockwise gyroscopic spin will increase the torque about the point of welding and in the other welding direction, it will decrease the torque (Figure 2.3). These torque differences, when applied to a welder's hand, will amount to differences in the ratio of kick to pressure, and the direction of these differences will depend on the direction in which the object is reoriented. This gives the gyroscope objects the potential to affect judgments of weight or length. Length perception is determined, in part, by the kick/pressure ratio (Carello et al., 1992; Hoisington, 1920; Lederman, Ganeshan, & Ellis 1996), but for rigid objects, these ratios do not change with the rotational velocity in the horizontal dimension as the gyroscope objects do. For weight perception, rotational inertia is a key object property. Although the gyroscope objects' moment of inertia remains unchanged when the gyroscope spins, its redirection of torques may feel like a resistance to rotation. Since weight perception has been



shown to be tied to movableness, and not just MOI or mass, it is very possible that spinning gyroscopes will feel heavier to perceivers. Likewise, experiences of object length, mass distribution, center of mass, and partial length could potentially be affected.

## Chapter 3: Experiment 1

### Gyroscopic forces and weight perception

There are several potential perception-action consequences of the gyroscope axle's resistance to rotation. Heaviness judgments entail movableness, as determined by task. That is, an object that is difficult to rotate is less moveable if the moving includes rotation rather than just translation. Resistance to rotation is quantified by an object's moment of inertia (MOI). While spinning gyroscopes might *feel* more resistant to rotation, MOI does not actually increase with spin. Strictly speaking, MOI as explained reflects the mass distribution of rigid bodies. The key feature of a gyroscope is that it has moving parts. A gyroscope's total MOI would then be the sum of at least two MOIs, one for the spinning disk and one for its frame. Importantly, the spin of a gyroscope does not change the object's CM or distribution of mass relative to it for either reference frame. In other words, MOI does not reflect  $L$ . So it is unclear what the action consequences of  $L$  will be. An initial conjecture is that since  $L$  resists a change in direction, increasing  $L$  will necessarily increase difficulty of movement. However, this resistance takes the form of redirecting forces rather than merely opposing them as MOI does. It is therefore unclear how this type of resistance will be perceived.

### Methods

**Participants.** Fifteen University of Connecticut undergraduates volunteered to participate as one option to fulfill a course requirement. All were right-handed.

**Materials.** Three gyroscope objects were constructed from 30 cm aluminum rods with 10 cm wooden handles. A salvaged brushless hard drive disk (HDD) motor was attached to the end of

each rod and 60 g disks were fitted to the motor hubs. Motors were wired to a driver board that allowed for adjustable spin rate and for both clockwise and counterclockwise spin. Maximum angular velocity of each gyroscope object was verified with a laser tachometer. One of the gyroscope objects was fitted with a 100 g vinyl weight, one with a 50 g weight, and one with no added weight. Weights were attached directly below the motor and disk assembly of the objects.

**Procedure.** The Institutional Review Board (IRB) of the university approved all experimental procedures. Participants received a summary of the study and gave their consent to participate. They were told that they would be making weight judgments about a series of wielded objects which they could not see. They were instructed to rate each object in comparison to a standard object, which they would wield before each trial. Participants sat with a curtain occluding their view of their right arms from the shoulder down. They extended their right hands through a curtain which blocked the view of their right arm from the elbow downward. Participants were handed the 50 g gyroscope object with a spin of 0 and instructed to wield it either in a forehand-backhand arc of  $45^\circ$ , or in a forehand-only arc of  $90^\circ$ , after which it was immediately retrieved from the participant's grasp by the experimenter. Participants were then instructed, "This is the standard object. All other objects should be judged in comparison to this object. Consider the standard object to have a weight of 100. That means if an object weighs half as much, you should rate it as 50, while an object weighing twice as much should be considered 200. You can use any number within or outside of that range to rate objects."

Next, participants were handed one of the three gyroscope objects which had been set to one of the three spin conditions: Clockwise, CW (733 rad/s), None (0 rad/s), or Counterclockwise, CCW (-733 rad/s). They were instructed to wield the object in exactly the same way as the standard object, giving their rating of its weight upon completing the wielding motion.



*Figure 3.1.* (A) Weight judgments by added mass and spin direction for forehand, 90° wielding mode. (B) For forehand-backhand, 45° wielding mode. Error bars indicate one standard error of the mean.

A  $3$  (spin)  $\times$   $3$  (mass)  $\times$   $2$  (mode) mixed effects ANOVA was conducted on weight judgments with participant as a random effect. The main effects of mass,  $F(2, 826) = 791.06, p < 0.001$ , and spin,  $F(2, 826) = 6.83, p < 0.01$ , were significant. Judged weight increased as weight increased, and as spin changed from CCW to CW. Although there was no main effect of wielding mode,  $F < 1$ , its influence was seen in the interaction with spin,  $F(2, 826) = 3.87, p < 0.05$ . In particular, spin's influence on judged weight was limited to the 90° forehand wielding mode (Figure 3.1).

## Discussion

We originally predicted that since angular momentum diverts the intended direction of wielding, this might be experienced as added resistance to rotation, similar to the effects of an increased MOI. Since MOI is implicated in weight judgment, we predicted that increasing angular momentum would increase weight judgment. However, there was no apparent effect of absolute angular momentum.

We additionally predicted that since weight at the end of an implement increases torque about the wrist during horizontal wielding, the effect of the gyroscope's angular momentum could depend on wielding direction. That is, when angular momentum is directed outward (due to a clockwise spin of the gyroscope, while viewed from the top) and the gyroscope object is wielded in a forehand direction by the right hand, the torque about the wrist induced by gravity on the end of the implement would be supplemented by the angular momentum of the gyroscope, but this torque would be negated somewhat when the wielding direction was reversed. In other

words, the direction of spin, not just absolute spin, would be important. This hypothesis was supported, as participants reported the object as heavier in the clockwise spin condition.

The interaction between wielding mode and clockwise spin further supported the notion that it was the added torque, not the diversion of the rotation direction, that caused the object to feel heavier. Plots indicate a clear separation between the different spin conditions in the forehand-only wielding mode, and no clear separation between them in the bidirectional wielding mode. This is somewhat surprising given that it has been shown that for some purposes, wielding to perceive object properties is effective under a considerable range of circumstances, suggesting that wielding mode should not matter. However, it has also been demonstrated that wielding motions, though varied, tend to maximize production of information relevant to a particular task (Harrison et al., 2011). The results of Experiment 1 demonstrate that constraining wielding motions to one direction in the horizontal dimension makes it difficult for the haptic perceptual system to register the added gravity-directed torque as independent from the added mass at the end of the implement.

The results of the experiment did not show that the increased “damping” resistance to rotation (harder to initiate, but easier to stop) affected weight judgments. Spin only affected weight judgments in the unidirectional wielding mode, but both modes allowed participants to experience both starting and stopping rotation. Only in the unidirectional wielding mode, however, did participants experience a different kick to pressure ratio that was not reversed during the second half of the trial. Therefore, this component of the wielding information is likely what drove the differences in judgments.

More broadly, this highlights the importance of reversibility of wielding motions for judgments of some object properties. In Harrison et al.’s (2011) studies, movement of objects

was constrained to rotation about a single axis, but movement was reversible, and participants were more or less accurate in their assessments. In Experiment 1, participants' weight judgments depended primarily on mass in the bidirectional wielding mode, while spin also contributed in the unidirectional wielding mode.

Experiment 1 addressed judgment of weight, which is only one property affected by an object's mass distribution. Judgment of other properties (e.g., shape, total length, and partial length above and below the grasp) are likely to be impacted by  $L$  as well. Length, in particular, is likely to be susceptible. During a horizontal sweep in our object testing (Chapter 2), as  $L$  changed so did the torque about the wielding axis. It has been shown that differences in torque about the wielding axis are entailed in changing the perceived extent of wielded objects (Hoisington, 1920; Carello et al., 1992). While the torque required for wielding increases with mass, length, and/or distance between grip and center of mass, thus increasing the magnitude of both, an increase in the ratio of kick to pressure is expected from an increase in the ratio between the below-hand and above-hand segments of a wielded rod. Further work is warranted in this area.

## Chapter 4: Experiment 2

### Perception of affordances of gyroscope objects

Experiment 1 indicated that gyroscopic motion can influence perception of object heaviness, at least when wielding is constrained to a single direction. As noted earlier, it has been suggested that judgments of heaviness are determined more by an object's *movability* than by its mass (Shockley et al., 2001, 2004). Two features of this latter finding are germane. First, they were obtained during free wielding. Second, the criteria of movability of an object are defined by task (Wagman & Shockley, 2011). In Experiment 1, participants' wielding motions were not free nor were they conducted in anticipation of any particular task.

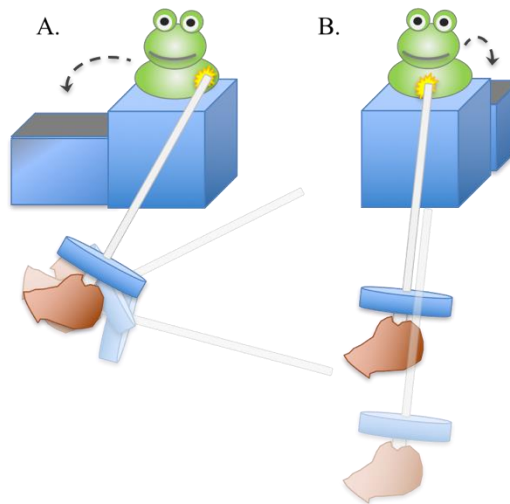
In Experiment 2, the focus was taken off weight *per se* as participants were asked to make judgments of an object's suitability for particular tasks. We created a gyroscope object that was constructed to fit either of two tasks. A *hitting task* was designed to maximize the production of gyroscopic reactive forces by requiring rotation of the object's long axis without requiring translation of the object. A *poking task* was designed to minimize the reactive forces by requiring translation without rotation. All judgments were obtained during free wielding. Since wielding motions are informative about intention to act and about perceiving strategies (Michaels, Weier, & Harrison, 2007), we additionally tracked motions for a subset of participants while they were assessing the objects for each task.



## Methods

**Participants.** Twenty-three undergraduate psychology students at the University of Connecticut volunteered to participate as one option to fulfill a course requirement. All were right-handed.

**Materials.** A gyroscope object similar to those in Experiment 1 was created, using the same mass and motor assembly mounted onto an aluminum rod with a wooden handle. The object was, additionally, fitted with a precision tip made of wooden dowel mounted onto the end of the gyroscope object as seen in Figure 4.1. The action task used a rubber toy frog approximately 6 cm tall  $\times$  6 cm wide  $\times$  4 cm deep as a target. The frog sat on platform, a wooden cube with sides measuring 11.5 cm. A 11.5 cm wide  $\times$  11.5 cm deep  $\times$  8 cm tall box served as a receptacle to catch the frog. It was placed flush against the platform, to the side for hitting or against the back for poking.



*Figure 4.1.* (A) In the hitting task demonstration, the gyroscope object is swung sideways to hit the side of the toy, knocking it into a box located next to the platform. (B) In the poking task demonstration, the gyroscope object is translated up and then forward to poke the toy into a box behind the platform.

Motions were tracked using an Optotrak Certus motion capture system. Three cameras, each with three sensors, were arrayed facing the participant's wielding arm which held a gyroscope object fitted with four sensors attached to a balsa wood frame.

**Procedure.** The University's IRB approved all experimental procedures. Participants received a summary of the study and gave their consent to participate. The experimenter demonstrated the two tasks. In hitting, the experimenter rotated a rod about his wrist, swinging it horizontally  $90^\circ$  in order to knock the toy frog off of the platform and into the box. In the demonstration, the experimenter executed the task entirely through rotation, minimizing translation of the wrist joint as much as possible. For poking, the experimenter poked the frog from the platform into the box. In this task, the starting position is 18 cm below and 8 cm in front of the frog's center of mass. In the demonstration, rotation was minimized so that the task was executed entirely through translation.

Participants were seated with their right arms extending through an occluding curtain. They were handed the gyroscope object spinning at 366 rad/s and were instructed to use it as the standard of comparison for their judgment of the next object's suitability for the designated task (whether poking or hitting). Although past studies obtaining judgments of suitability used a 7-point scale (Michaels et al., 2007; Wagman & Carello, 2001), this procedure was modified to reflect the use of a standard object as in Experiment 1. Participants were instructed to consider the standard object as a 10 in suitability, with objects considered less suitable than it to be rated lower, and objects considered more suitable than it to be rated as higher. Participants wielded the standard object for as long as they chose, usually 3–10 s, while motion of the tool was recorded. For exceptionally long wielding bouts, only the first 20 s of the motion capture were used.

When participants finished wielding the standard object, the experimenter retrieved it, set the gyroscope to the trial condition speed (0, 366, or 733 rad/s), returned it, and instructed the participant to wield it and rate its suitability for the designated task. The study followed a 3 (spin speed)  $\times$  2 (task) within-subjects design. Participants completed three trials of each of the six conditions, which were randomly ordered.

## Results

**Ratings.** A 3 (spin speed)  $\times$  2 (task) mixed effects ANOVA was conducted on suitability ratings with participant as a random effect. There was no significant main effect of task,  $F < 1$ , indicating that judgments of suitability were similar for the two tasks. There was a significant main effect of spin,  $F(2, 381) = 4.151$ ,  $p < 0.05$ . A post-hoc Tukey test indicated that while the no spin condition was significantly lower than the 366 rad/s condition ( $p < 0.05$ ) and the 733 rad/s condition ( $p < 0.05$ ), the two spin conditions did not significantly differ from each other. The Task  $\times$  Spin interaction was not significant,  $F < 1$ . Mean ratings are shown in Figure 4.2.

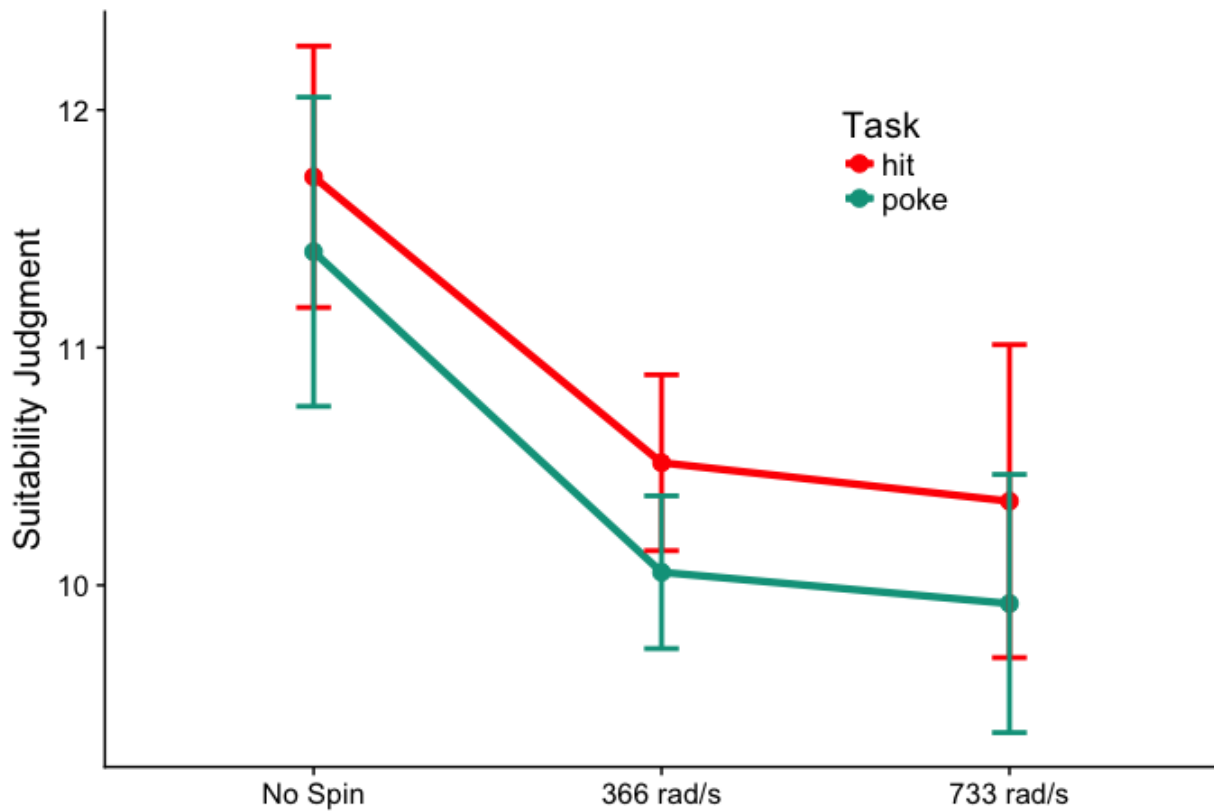


Figure 4.2. Suitability ratings as a function of task and spin rate.

**Motion Analysis.** Motion tracking of the gyroscope object in the experiment outlined above required additional an additional experimenter, so motion was tracked on trials of only a portion (8) of the participants. A 3 (Spin rate)  $\times$  2 (Task)  $\times$  2 (Standard object versus test object) within-subjects ANOVA was conducted on wielding duration. There was a significant main effect of spin rate,  $F(2, 278) = 5.726, p < 0.05$ , showing that as spin increased, participants spent longer wielding the objects. There were no other significant main effects or interactions (Figure 4.3).

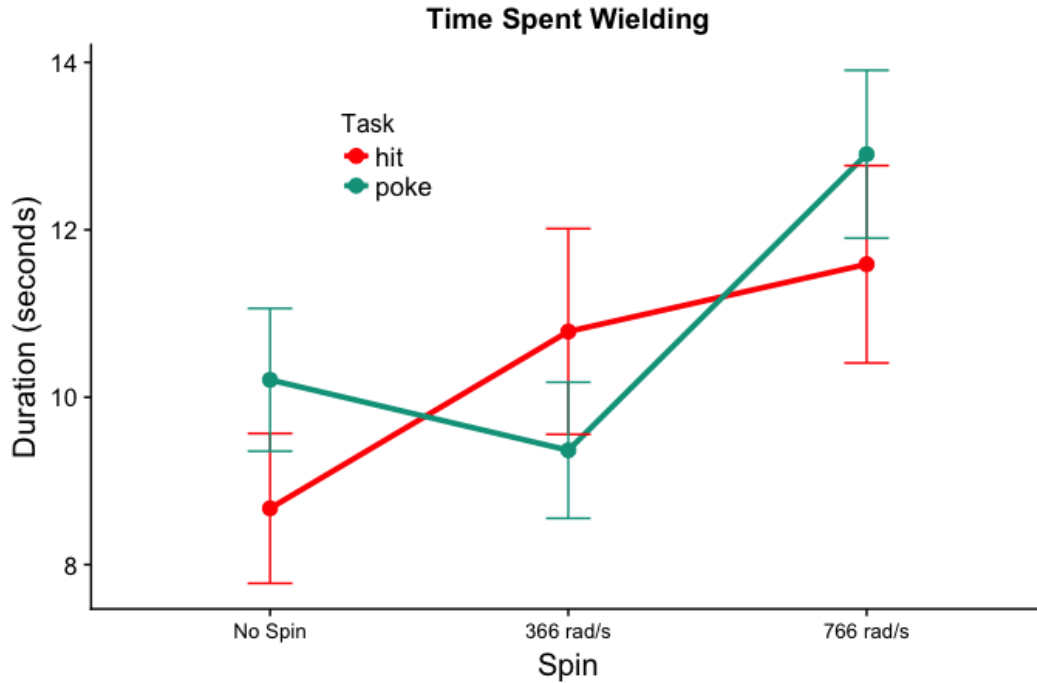


Figure 4.3. Movement durations wielding the standard and test objects for each task under three different spin conditions.

In order to characterize the change in object orientation relative to a fixed coordinate system, Euler angles were analyzed (Michaels, Weier, & Harrison, 2007). Euler angles for each axis were smoothed with a first-order low pass Butterworth filter with an upper critical value of 0.04 Euler deg/s. Change in angle at each 100 Hz time step was calculated and these were totaled for each axis of each trial (Figure 4.4). A 3 (spin velocity)  $\times$  2 (task)  $\times$  3 (axis) within-subjects ANOVA conducted on rotation totals revealed main effects of spin velocity,  $F(1, 851) = 6.80$ ,  $p < 0.01$ ; axis,  $F(2, 851) = 83.21$ ,  $p < 0.001$ ; and task,  $F(1, 851) = 16.69$ ,  $p = 0.001$ . The interaction of axis and task was marginally significant,  $F(2, 851) = 2.40$ ,  $p = 0.091$ . No other interaction effects were significant.

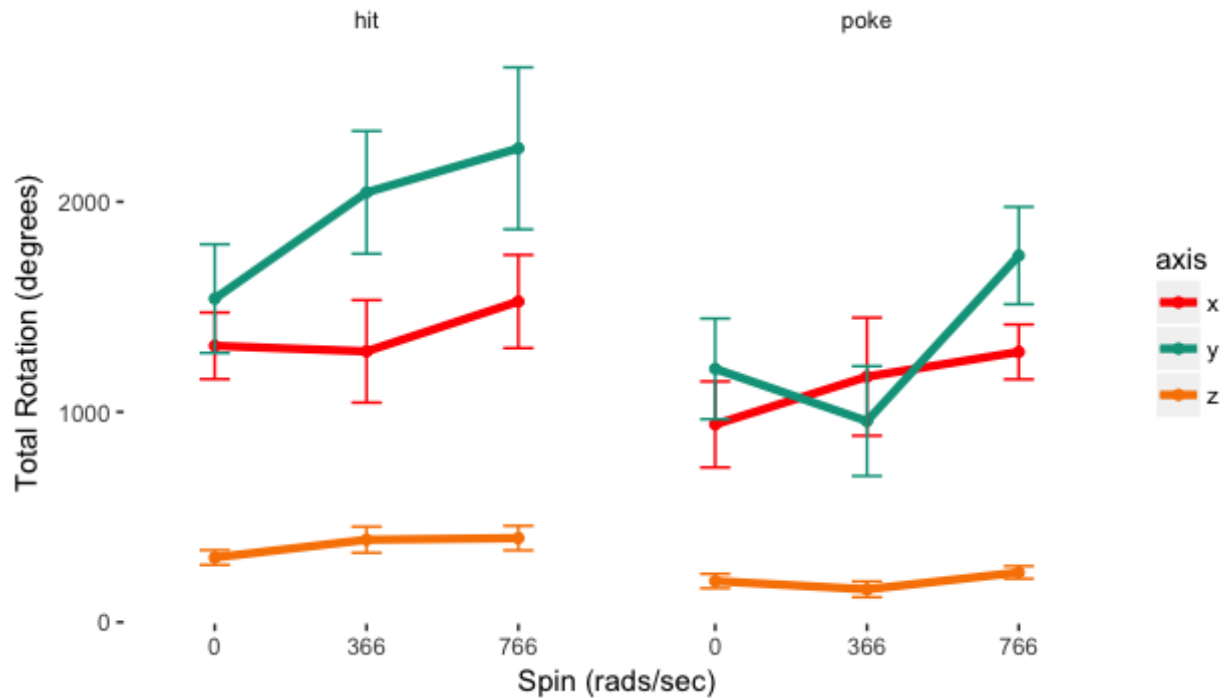


Figure 4.4. Rotations about each axis as a function of spin speed and task.

Rotations about the z-axis were minimal relative to those of the other dimensions, and did not change across conditions. This is not surprising, since such rotations are neither required by the two tasks nor do they generate gyroscopic reactive forces. Generally, orientation in the other two dimensions increased with spin rate, and changed more for hitting than for poking, with a suggestion that the change about the y-axis—the hitting axis—was more dramatic for hitting. There were additionally a large number of rotations about the x-axis compared to the z-axis. While no rotation is required about either axis for either task, rotations about the x-axis generate information about one of the factors being changed across trials (gyroscopic spin), while rotations about the z-axis do not. However, this was seen regardless of whether the information was task-relevant (i.e., for hitting) as well as not task-relevant (i.e., for poking).

## Discussion

As predicted, participants generally perceived the devices as less suitable as spin was increased. Since gyroscopes produce a novel force field for wielding, this difference in suitability judgments was probably due to a general lack of experience in using devices with substantial added angular momentum for common tasks. This is corroborated by wielding durations: It seems that participants used additional time exploring the perception-action space when the feel of the objects was especially unfamiliar. The analysis of rotations also supported this to some degree. While participants did perform more rotations about the y-axis (essentially, practice hitting motions) in the hitting task, they also demonstrated a tendency to explore gyroscopic forces even in the poking task, when such forces were not entailed. This further suggests that participants made general ratings of suitability to some extent and did not entirely differentiate between the two tasks in their judgments.

## Chapter 5: Experiment 3

### Effects of gyroscopic motion on performance

Experiment 2 demonstrated that while angular momentum ( $L$ ) has some unique perceptual consequences, it shares some characteristics with mass distribution. Specifically, the effects of  $L$  on weight perception observed in Experiment 1 follow a similar pattern as  $L$ 's effect on judgment of object suitability, suggesting that the movableness of an object is part of what drives weight judgments (Shockley et al., 2001, 2004). However, contrary to our predictions based on this research that movableness is task-specific rather than general, this effect was observed both when angular momentum was entailed in the task via rotation (hitting) and when it was not (poking).

One possible reason for this is that gyroscope  $L$ , which has not been studied from an affordance standpoint, might be implicated in object translation in a non-obvious way. For example, if small-scale, incidental rotations occur in a translation task, these might impart non-negligible torques on the handle of the object which disrupt execution of the task.

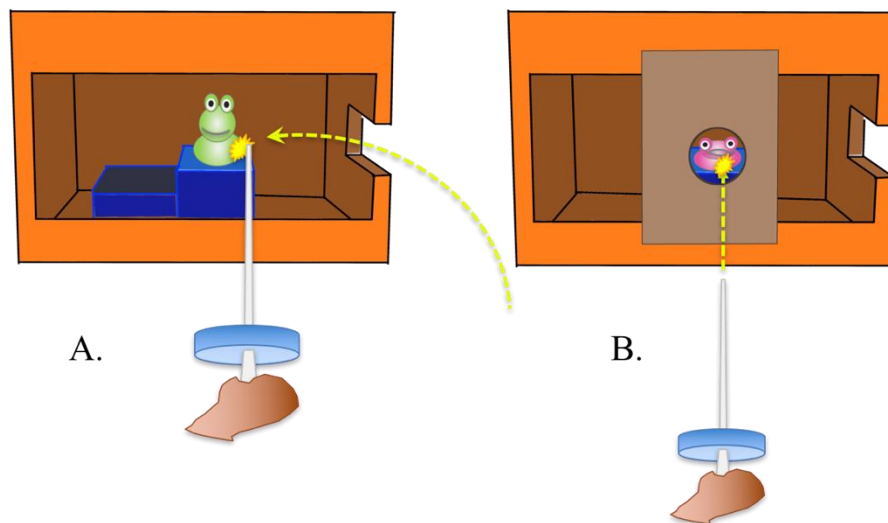
Alternatively, judgments of object properties in Experiment 2 happened at some remove from the task. While participants did receive a practical demonstration of hitting and poking, they did not execute these tasks themselves, nor were the implements of the task visible during their judgments. Additionally, the requirement that participants shift back and forth between the target tasks for many of the trials could have caused them to make a somewhat general assessment for the implement in each trial rather than an assessment specific to just one of the tasks. To test for this possibility, Experiment 3 was designed so that the hitting and poking tasks were actually performed under different spin conditions.



## Methods

**Participants.** Fifteen undergraduate students at the University of Connecticut volunteered to participate as one option to fulfill a course requirement. Five graduate students volunteered to participate without compensation. All participants were right handed. Verbal reports of task difficulty were collected for these participants plus four additional pilot participants.

**Materials.** The gyroscope object in Experiment 2 (rod-mounted gyroscope fitted with a precision tip) was used in the execution of the hitting and poking tasks. In addition to the toy frog and platform from Experiment 2, barriers were placed around the platform so as to increase the difficulty of the tasks (Figure 5.1). For hitting, a slot limited participants' ability to correct the object's trajectory towards the frog. For poking, a 6.5 cm circular aperture 5 cm in front of the frog required a longer directed poking motion. A smaller target (shown as pink in Figure 5.1) was provided in the poking task to make the task's difficulty comparable to that of the hitting task.



*Figure 5.1.* (A) In the hitting task, participants swung the gyroscope object through an aperture on the side of a barrier to hit the side of the toy, knocking it

into the box. (B) In the poking task, participants translated the gyroscope object up and then forward to poke through an aperture, knocking the toy into a box.

Trials were considered successful if they were executed within a 750 ms interval, no collisions with the barriers occurred, and they resulted in the toy landing in the box. To ensure that participants executed the task within the required 750 ms time window, an audio track was created using a web-based sequencer. A 523.25 Hz (note C5) sine wave sounded for 125 ms, prompting the initiation of the task attempt, followed by 500 ms of silence, and then the sine wave was repeated to mark the end of the attempt. Trials in which the frog was not impacted before the conclusion of the second tone were recorded as unsuccessful. Participants were informed when task executions were considered successful.

**Procedure.** Participants received a summary of the study and gave their consent to participate. The hitting and poking tasks were explained and demonstrated by the experimenter, with the caveat that a task had to be completed within a 750 ms interval in order to be considered a success. As the hitting task was demonstrated, it was emphasized that the task should be completed by rotating the implement, with translation minimized as much as possible. Participants held the gyroscope object fitted with the precision tip at an angle parallel to the box enclosing the frog, such that a 90° rotation would be required to execute a successful hit. As the poking task was demonstrated, the experimenter took care to minimize rotation of the object. Participants held the gyroscope object fitted with the precision tip perpendicular to the box, pointed at a “home” sticker located 14 cm below the level of the platform, with the implement’s long axis kept level with the ground, then moved the object upwards and then forwards in order to execute a successful hit. The experimenter sat on the opposite side of the box and recorded the outcome of trials. For each attempt, a research assistant would say “Ready,” and then initiate the

audio cue track. Participants attempted the designated task. The frog was replaced on the platform before the next trial as needed.

There were 12 trial blocks total for each participant. Blocks were paired combinations of each task (hit and poke), and each pair was pseudo-randomly assigned a spin velocity. The task order in each second instance of spin velocity was reversed. Pairs were preserved across each participant, but the order of the pairs was randomized. Thus, two typical trial blocks might be ordered as in Table 5.1. Each block consisted of 18 trials, but a block was concluded early if a participant reached a criterion of 3 consecutive successful trials. At the end of the experiment, participants were asked whether they found the gyroscope's spin to be helpful, detrimental, or neither helpful nor detrimental to their performance of each task.

*Table 5.1. Two example trial block schedules.*

Participant	Blocks 1-2	Blocks 3-4	Blocks 5-6	Blocks 7-8	Blocks 9-10	Blocks 11-12
1	733 rad/s Hit, Poke	0 rad/s Hit, Poke	733 rad/s Poke, Hit	366 rad/s Poke, Hit	0 rad/s Poke, Hit	733 rad/s Hit, Poke
2	366 rad/s Poke, Hit	0 rad/s Poke, Hit	366 rad/s Hit, Poke	733 rad/s Poke, Hit	733 rad/s Hit, Poke	0 rad/s Hit, Poke

## Results

**Task Performance.** Performance was assessed as the number of unsuccessful attempts made per trial before reaching criterion or completing 18 trials, whichever came first, with higher performance being indicated by a lower score. A 3 (spin speed)  $\times$  2 (task) mixed-effects ANOVA was conducted for this measure. Overall, performance met criterion in fewer trials when poking ( $M = 1.934$ ,  $SE = 0.31$ ) than when hitting ( $M = 1.34$ ,  $SE = 0.22$ ), but this difference did not reach significance,  $F(1, 21) = 2.274$ ,  $p = 0.133$ . The main effect of spin velocity was significant,  $F(2, 21) = 4.99$ ,  $p < 0.01$ , indicating that participants required the fewest trials to reach criterion when spin was absent ( $M = 0.77$ ,  $SE = 0.27$ ), the next fewest at 366 rad/s ( $M =$

1.70,  $SE = 0.32$ ) and the most at 733 rad/s ( $M = 2.45$ ,  $SE = 0.43$ ). The significant interaction between spin velocity and task type,  $F(2, 21) = 4.126$ ,  $p < 0.05$ , is shown in Figure 5.2. A post-hoc Tukey test indicated that the highest spin rate makes hitting more difficult ( $p < 0.05$ ), but did not confirm that spin rate affected performance on the poking task.

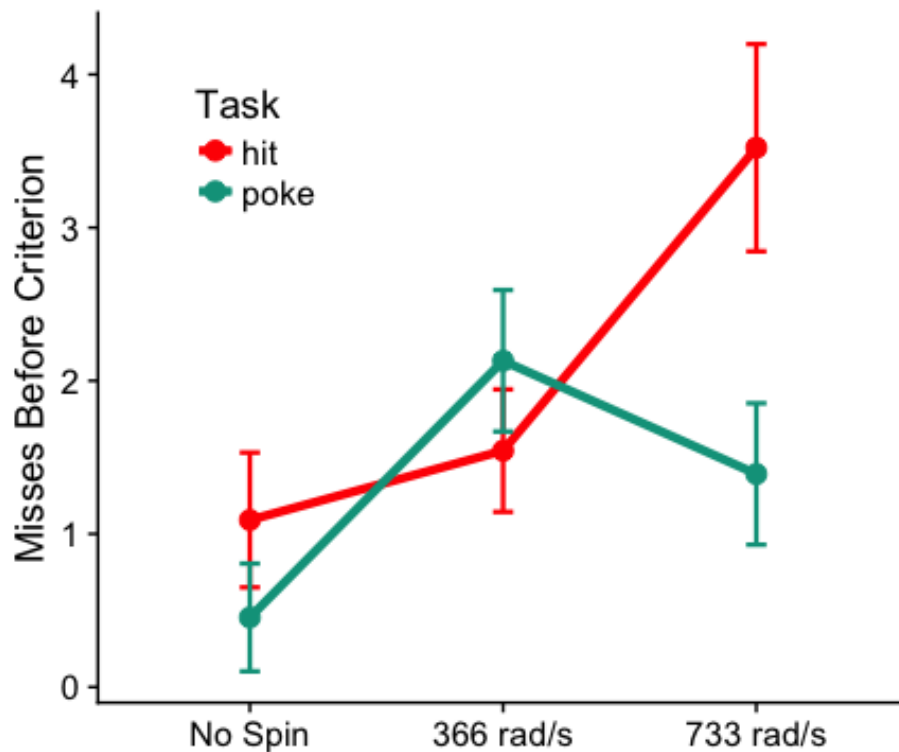


Figure 5.2. Number of misses as a function of spin rate and task.

**Participant reports.** Whereas most participants ( $n = 18$ ) reported that added spin made the hitting task more difficult, the same number reported that the poking task was not more difficult. This difference was significant,  $\chi^2(1) = 4.571$ ,  $p = 0.03251$ .

## Discussion

As predicted, increasing spin increased the difficulty of the hitting task. This is consistent with their ratings of object suitability in Experiment 2. However, contrary to those suitability

ratings, the poking task was not shown to become more difficult as spin velocity was increased. More participants reported that increased spin velocity was detrimental to their performance on the hitting task than on the poking task. This suggests that ratings of object suitability and wielding times for the two tasks may have reflected a general notion of controllability rather than a task-specific one.

Another component of the discrepancy between the results of Experiments 2 and 3 might reside in wielding times. Whereas participants arrived at suitability ratings after 10 s or so of wielding in Experiment 2, they were necessarily limited to 750 ms during task execution in Experiment 3. The effects of gyroscopic forces on performance might emerge over the course of multiple trials or prolonged wielding, either of which allow for learning. To address this possibility, Experiment 4 implemented an orienting task that allows for evaluating continuous improvement over time.

## Chapter 6: Experiment 4

### Perception-Action tuning to gyroscopic forces

Participants in Experiment 1 treated the added angular momentum as additional weight only when the  $L$  supplemented gravitational torque. This, in turn, occurred only when their wielding motion was not reversed nor, by extension, was the direction of  $L$ 's added torque. In Experiment 2, it was further shown that angular momentum can also affect judgments of object suitability for certain tasks. It also seems that participants have some awareness of this and accurately report an object's suitability for certain tasks, recognizing which tasks are made more difficult by the spin and which are not. Experiment 4 will further differentiate the perception-action implications of added angular momentum from those of the more studied added mass by requiring participants to perform a task that requires ongoing object reorientation under changing conditions of added mass and added gyroscopic spin.

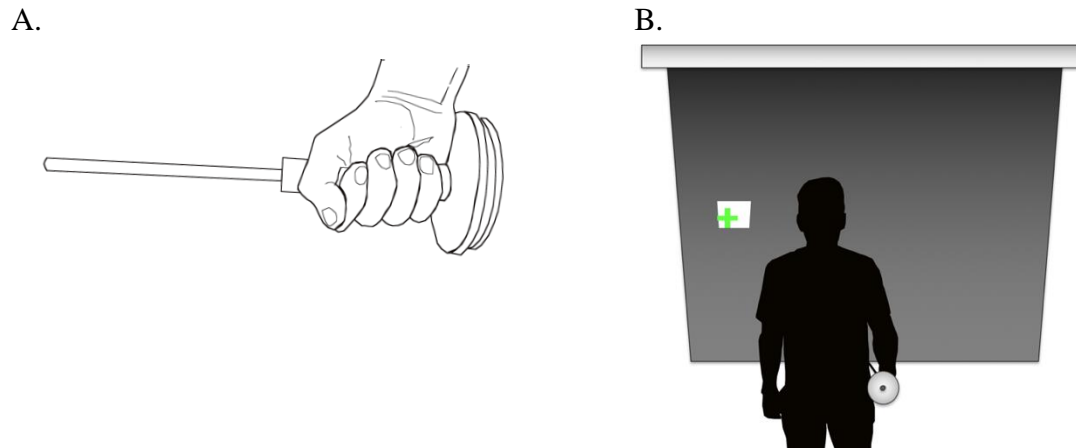
One limitation of the affordance task of Experiment 2 is that the relatively small changes to the force fields required to execute the poking and hitting tasks might have been too insubstantial to impact performance, given the perceptual system's ability to compensate for perturbations (Marsden, Merton, & Morton, 1976; Turvey, 2007). In Experiment 4, dependent variables are drawn from a high-resolution time series of movement data, supporting analysis of much smaller perturbations and their subsequent corrections.

## Methods

**Participants.** Sixteen participants included eight University of Connecticut undergraduates who volunteered to participate as one option to fulfill a course requirement and eight graduate students who volunteered to participate without compensation. All were right-handed.

**Materials.** A gyroscope object was constructed consisting of a cylindrical wooden handle (12 cm long with a radius of 1.125 cm) fitted to a 20 cm hollow aluminum rod. Below the handle was an HDD brushless DC motor with two 30 g platters to serve as the gyroscope's flywheel. A wood composite disc was placed between the handle and motor to prevent the participant's hand from touching and slowing the flywheel (Figure 6.1 A). The aluminum rod, which extended 8 cm beyond the top of the handle, served as a "pointer" and was fitted with four Optotrak Certus (Northern Digital, Inc.) motion markers. Three cameras were used to track the markers. A Microsoft Visual studio program synchronized the motion capture data to create a visible marker of the pointer's aim; the intersection of the pointer's heading with the plane of the projection screen (1.5 m × 2.4 m) was rendered on the screen as a green cross.

The computer program displayed a white target square which oscillated across a 122 cm straight line trajectory either vertically or horizontally at a rate of 30 oscillations per minute as a sine function of elapsed time (Figure 6.1 B).



*Figure 6.1.* (A) The gyroscope pointer object. (B) The horizontal condition of the tracking task.

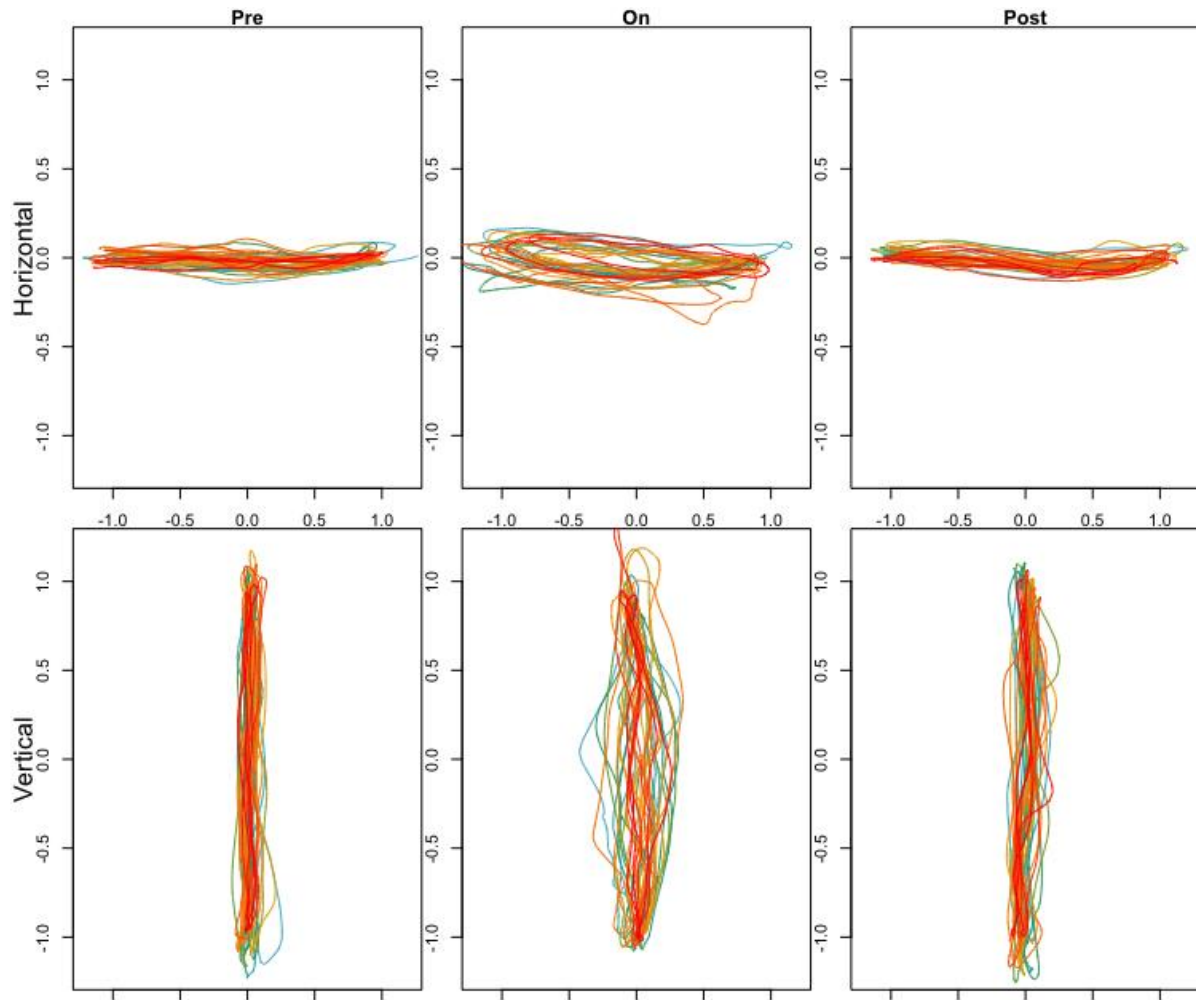
**Procedure.** Participants received a summary of the study and gave their consent to participate. They stood facing the screen 122 cm away, such that the right arm was aligned with the center of the screen. Participants held the gyroscope object in their dominant hand in a relaxed stance, with the arm down at their side, and with the pointer end of the object directed toward the screen. Participants were told that they were to track the white target square with the green cross as the target moved back and forth. Thus, the experience of pointing the object at the screen was akin to pointing a laser pointer. In the horizontal condition, the white square traversed a left to right linear trajectory as a sinusoidal function of time, at a rate of 30 Hz for each complete oscillation. In the vertical condition, the trajectory was up and down. In each orientation, the trajectory was 120 cm in length. Participants tracked the square for 2 min with the gyroscope off, then took a 15 s break while the experimenter either turned on the gyroscope (733 rad/s) or attached a weight (50 g) to the gyroscope assembly on the side opposite the participant's hand. The participants then tracked the square again for 2 min, after which they took another 15 s break while the experimenter turned off the motor to stop the flywheel or removed the weight. Participants then tracked the target for 2 min more. All participants



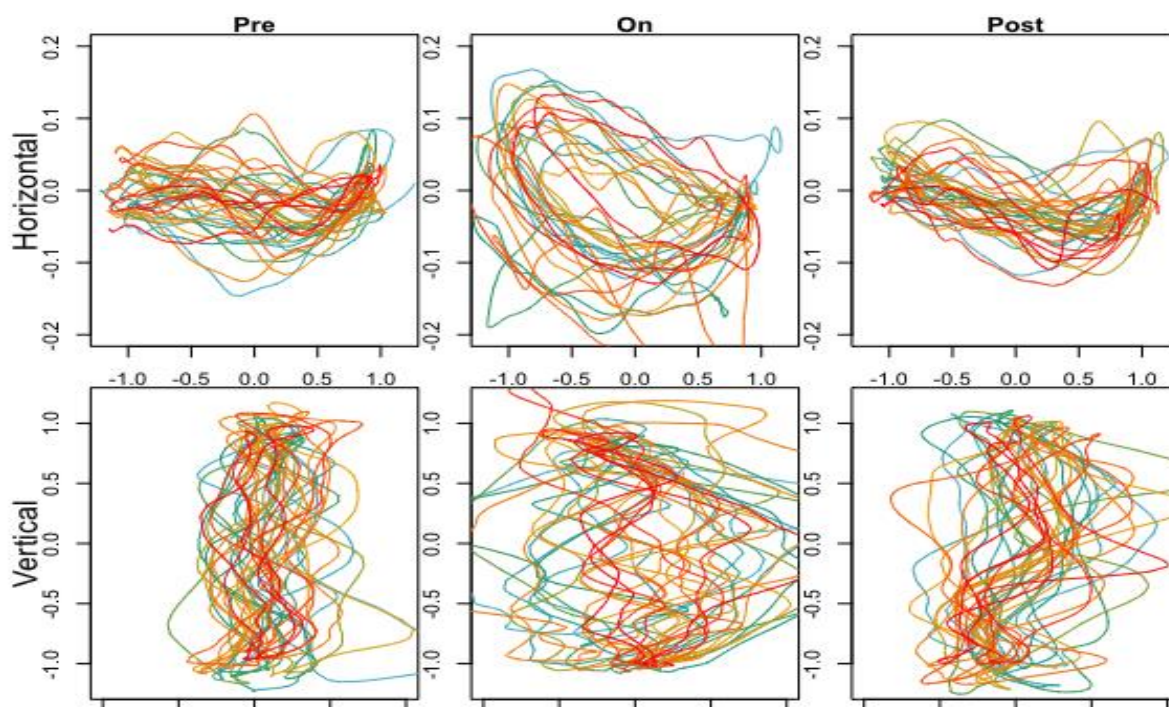
completed both the horizontal and vertical orientations for both the weight and gyroscope conditions. The order of the combinations of trials was counterbalanced. Throughout each trial, the locations of the green cross and white square were recorded.

## **Results**

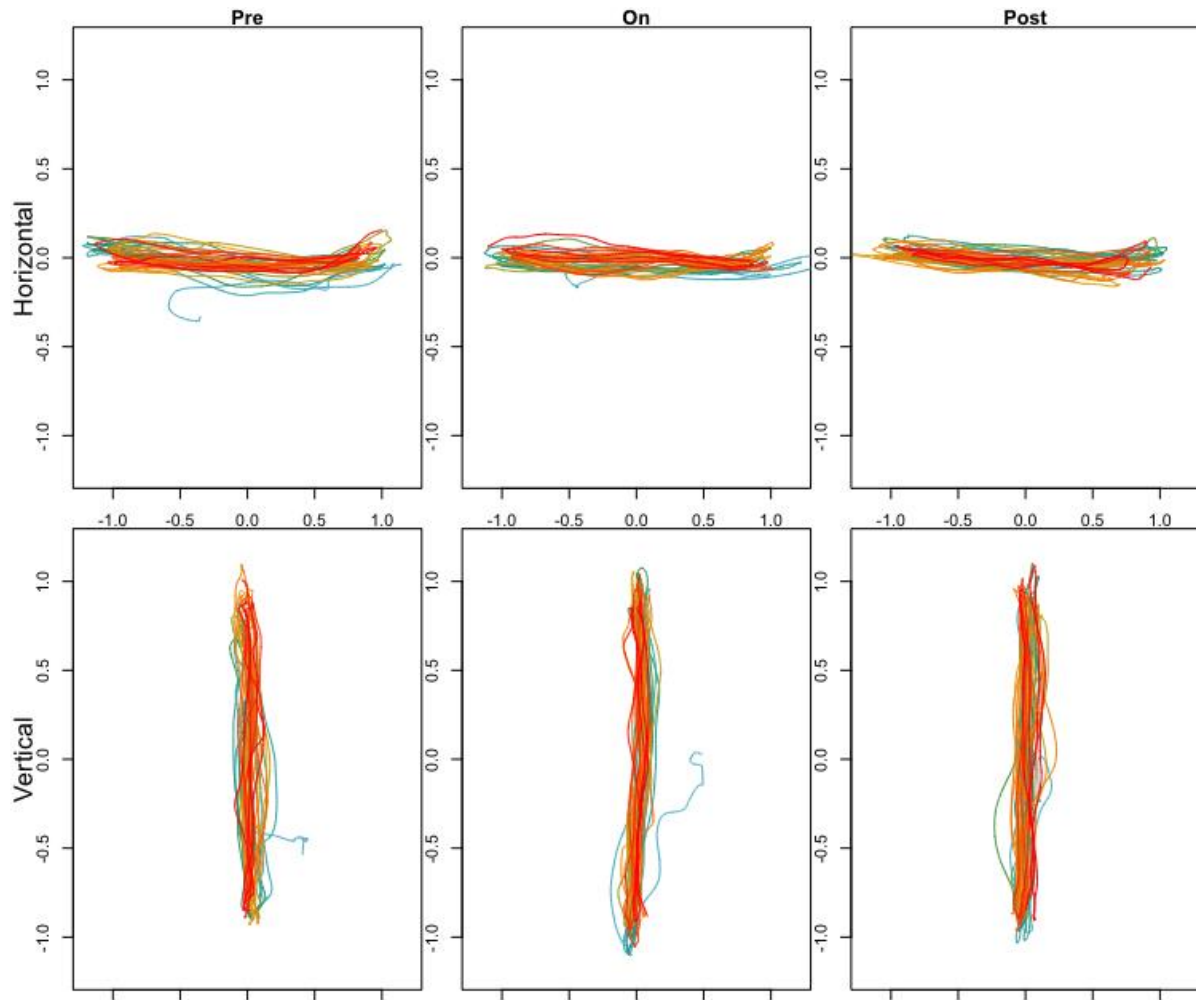
**Movement trajectories.** Trajectories of each stage of the task were plotted for the gyroscope trials and the weight trials (Figures 6.2 and 6.3, respectively). Since effects are expected to be strongest at the beginning of each stage, only the first 8 oscillations were plotted. The plots suggest that the vertical condition was more difficult.



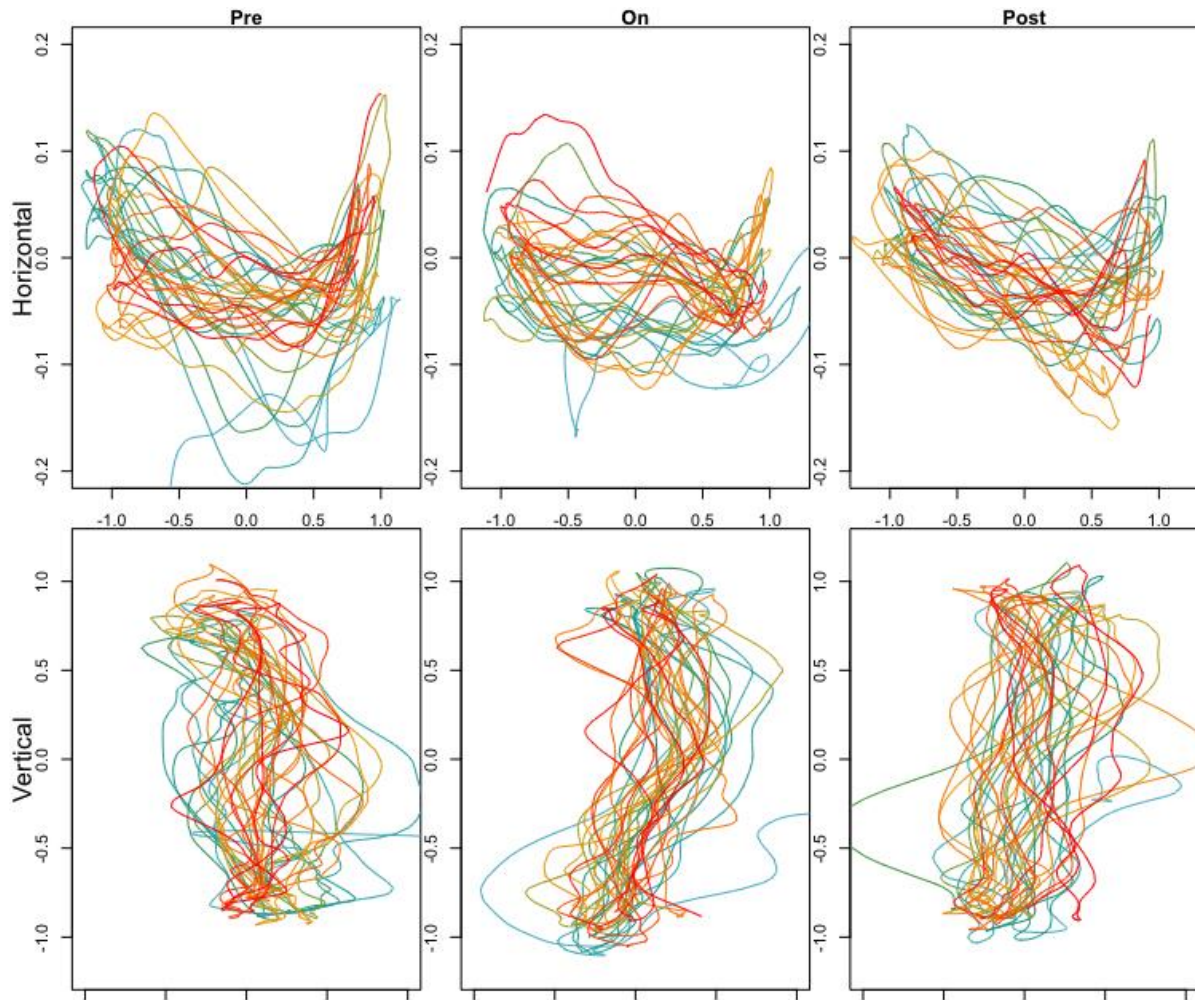
*Figure 6.2.* Representative trajectories for the horizontal (top row) and vertical (bottom row) orientations in the gyroscope condition. The gyroscope has not been turned on (left), is spinning (middle), or has been turned off (right). Each trajectory is limited to the first 20 oscillations. Color indicates time, turning from aqua (earliest), to yellow, to red (latest). See Appendix for 3D plots of these same trajectories.



*Figure 6.3.* The same trajectories as in Figure 6.1, but with the Y (top row) or X (bottom row) axis expanded.



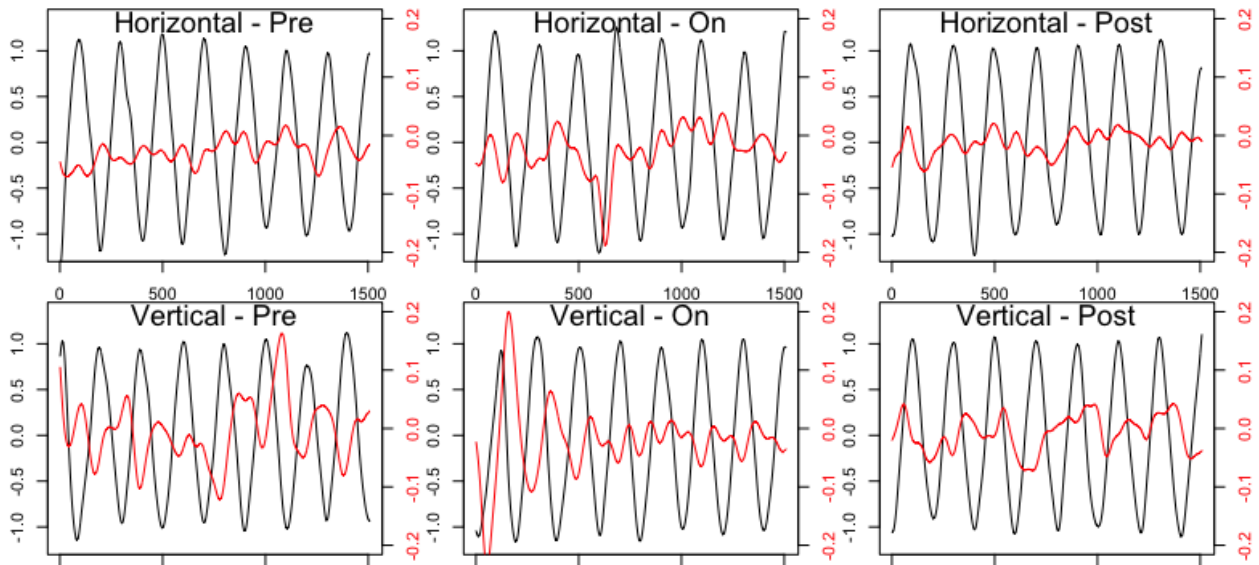
*Figure 6.4.* Representative added weight trajectories for the same participant as in Figures 6.2 and 6.3. The weight has not been added (left), has been added (middle), or has been removed (right). Each trajectory is limited to the first 20 oscillations. Color indicates time, turning from aqua (earliest) to yellow, to red (latest). See Appendix for 3D plots of these same trials.



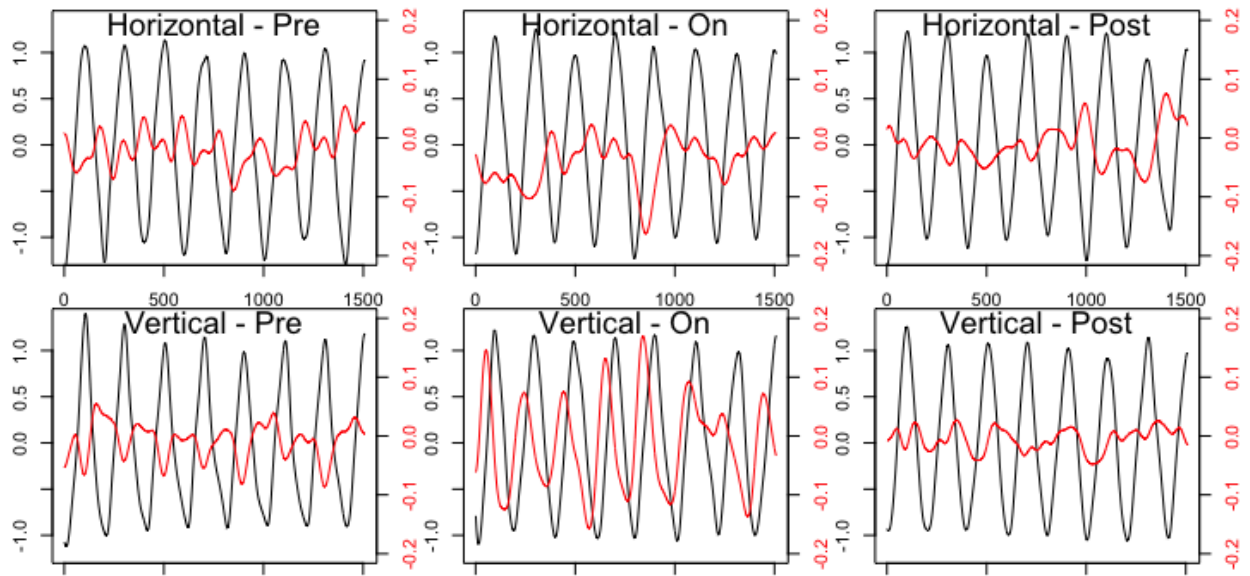
*Figure 6.5.* The same trajectories as in Figure 6.4, but with the Y (top row) or X (bottom row) axis expanded.

To inspect the diversions from the trajectory, the pointer's position in the dimension of the target's motion was overlaid on a plot of its position in the orthogonal dimension for the two conditions (Figures 6.6 and 6.7). Gyroscopic reactive forces are strongest at the zero crossing of the trajectory in the target dimension. This is especially apparent in the first several oscillations of the “Vertical – On” trial, where diversion in the orthogonal dimension is at its maximum and minimum at zero crossings of location in the trajectory dimension. Since gyroscopic reactionary forces occur in a direction orthogonal to applied torques, we anticipated oscillations in the

orthogonal dimension that were antiphase with oscillations in the target trajectory dimension for the “on” phase of the gyroscope condition. While some participants’ trials showed this, the effect was not apparent for all.



*Figure 6.6.* Target trajectory dimension (black) and orthogonal dimension (red) of pointer location over time for one illustrative participant in the Gyroscope Condition.



*Figure 6.7.* Target trajectory dimension (black) and orthogonal dimension (red) of pointer location over time for one illustrative participant in the Weight Condition.

**Perceptual Tuning.** Since gyroscopic reactive torques are anisotropic for wielding direction (see Chapter 1), diversion of the pointer from the target trajectory was calculated with respect the direction of each zero crossing of the pointer's location on the dimension of the target's motion. For example, in the horizontal condition, diversion at a positive-to-negative zero crossing was calculated as the pointer's current location in the y-dimension, and for a negative-to-positive zero crossing, it was calculated as the location in the y-dimension multiplied by  $-1$ . The values for each pair of zero crossings was averaged to create a single value of diversion for each full oscillation. It was hypothesized that in the gyroscope condition, diversion would be increased when the gyroscope was spinning (On phase) and decreased after it had been turned off (Post



phase), and that these effects would diminish over the course of the trial. Therefore, our first model equation included the Gyro condition (Weight vs. Gyroscope), trial phase (Pre, On, and Post), and the time variable (represented by Oscillation) as predictors. Results indicated that while many of significant interaction terms included the Gyroscope factor, several did not, suggesting that adding weight might have had a similar effect on diversion as gyroscope spin (Table 6.1). This was unexpected, considering diversion was calculated assuming that force field anisotropies exist only in the Gyroscope condition. However, a plot of the factors' effects on Diversion across oscillations suggests that the gyroscope's influence was different across orientations (Figure 6.8). This suggests that effects of Orientation might be suppressing the effect of gyroscope spin.

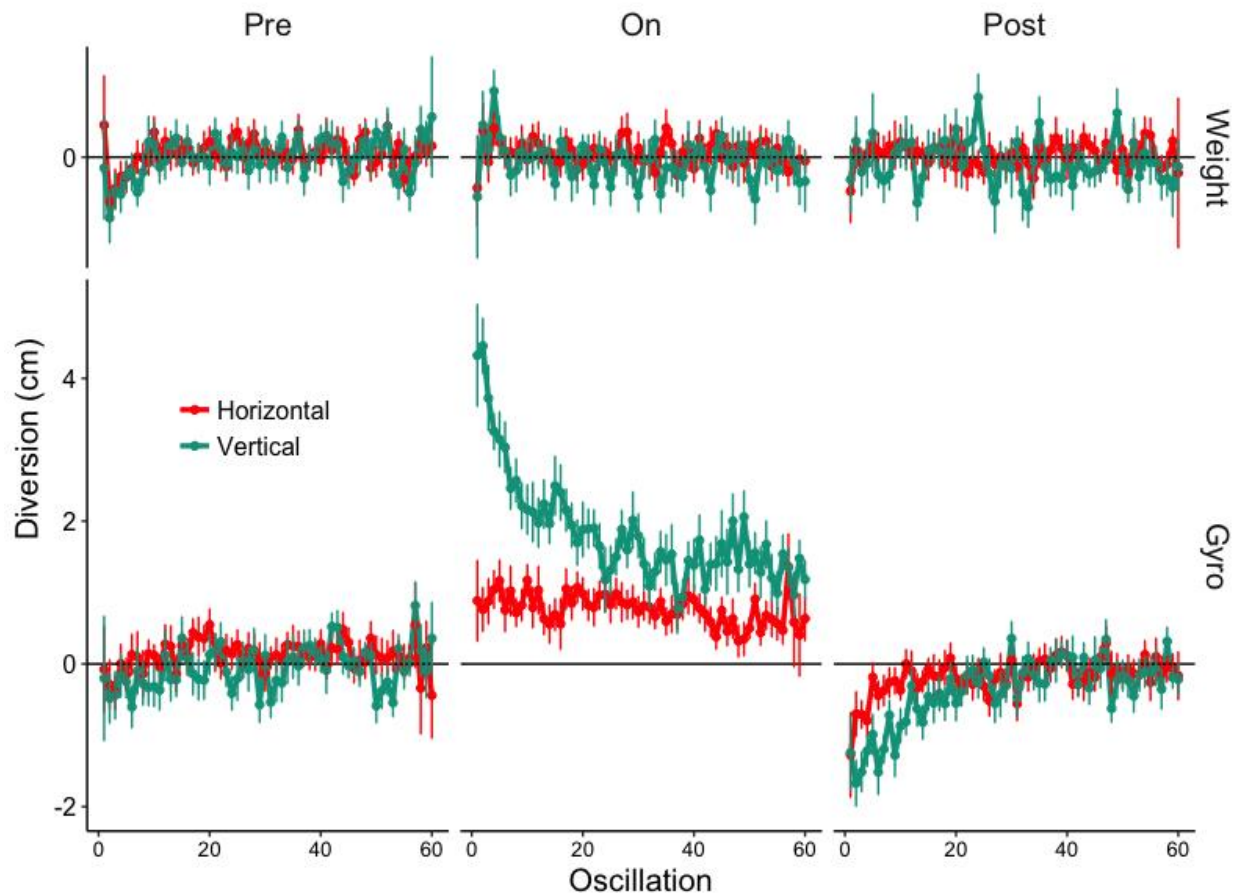
Table 6.1

*Diversion in Pre Phase of the Added Weight Condition Compared to the Other Two Phases of the Weight Condition and the Three Phases of the Gyroscope Condition.*

<b>Term</b>	<b><i>t</i></b>	<b><i>df</i></b>	<b><i>p-value</i></b>
Oscillation	2.54	69.34	< 0.05
Gyroscope	-0.03	2.201e+04	<i>n.s.</i>
On Phase	2.30	2.201e+04	< 0.05
Post Phase	1.58	2.201e+04	<i>n.s.</i>
Oscillation * Gyro	0.24	2.201e+04	<i>n.s.</i>
Oscillation * On	-2.81	2.201e+04	< 0.01
Oscillation * Post	-2.41	2.201e+04	< 0.05
Gyro * On	18.472	2.201e+04	< 0.001



Gyro * Post	-7.18	2.201e+04	< 0.001
Oscillation * Gyro * On	-5.96	2.201e+04	< 0.001
Oscillation * Gyro * Post	4.96	2.201e+04	< 0.001



*Figure 6.8.* Diversion from trajectory in the Pre, On, and Post phases of each orientation in the added weight condition and the added spin condition. Diversion units (see text) refer to distance on the projection screen. Error bars indicate one standard error of the mean.

A second model was created that included Orientation as a predictor (Diversion ~ Orientation \* Phase \* Gyroscope \* Oscillation). In this model, there were no significant main effects, and all significant interaction effects included the Gyroscope vs. Weight variable (Table 6.2).

Additionally, unlike the prior model, there were no significant effects that did not include either the On or Post trial phase terms. This is consistent with the assumption that all Pre trial phase conditions were equivalent. A Chi-square comparison of the two models indicated that the second model provided a significantly better fit,  $\chi^2(12) = 642.26$ ,  $p < 0.001$ .

*Table 6.2*

Diversion in the Horizontal Pre Phase of the Added Weight Condition Compared to the Other Conditions of Phase, Weight, and Orientation.

<b>Term*</b>	<b><i>t</i></b>	<b><i>df</i></b>	<b><i>p-value</i></b>
Gyro * On	5.65	2.2e+04	< 0.001
Gyro * Post	-3.81	2.2e+04	< 0.001
Gyro * Oscillation * Post	1.92	2.2e+04	0.056
Gyro * Orientation * On	10.78	2.2e+04	< 0.001
Gyro * Orientation * Post	-1.85	2.2e+04	0.064
Gyro * Oscillation * Orientation * On	-4.50	2.2e+04	< 0.001
Gyro * Oscillation * Orientation * Post	2.28	2.2e+04	< 0.05

*\*Only significant and marginally significant terms are shown.*

## **Discussion**

It was hypothesized that the initial effects of a gyroscope's forces would make the tracking task more difficult for spin trials, and this would equally affect both orientation conditions. Contrary to this expectation, orientation was a stronger predictor of error in the two spin conditions and did not appear to affect the pre- and post-spin conditions to the same degree. Additionally, we anticipated that for both orientations, the spin and post-spin conditions would be characterized by a substantial reduction in error over time. This hypothesis was supported.

These results indicate that gyroscopic reactive forces redirect the torques imposed by wielders so as to push the tip of the object away from its intended trajectory. Additionally, there is evidence that a period of retuning is required when the gyroscopic forces are discontinued. The persistence and directional nature of this retuning is comparable to that seen in prism adaptation (Redding, Rossetti, & Wallace, 2005), and sets it apart from the retuning process required by a change in object weight.

The reason for the effect of orientation is unclear. However, one possibility is that in the vertical condition, the gyroscopic reactive forces were produced in directions that were orthogonal to gravity. In the horizontal condition, participants needed to supply a constant torque in the frontal plane to support the pointer against gravity as well as a variable torque in the transverse plane to track the horizontal trajectory of the target square. While the gyroscopic forces generated in the spin conditions were variable, they were supplied in the transverse plane which was already entailed in the task before the gyroscope started spinning. In the vertical condition, the torque supplied by the participant to track the target square was in the frontal plane, or the same plane in which the counter-gravitational torque was supplied. Therefore, the participant was required to extend control from just one plane to two, imparting a greater degree of difficulty between the trials in which the gyroscope was on versus off.

Whether participants would continue reducing diversion over the course of a longer gyroscope trial is uncertain. After an initial dramatic period of diversion reduction in the vertical condition of the gyroscope phase, the correction appears to level off between 1–2 cm from 0. However, there appears to be a slight trend toward further reduction in both the later stages of the On phase of the vertical condition and the entire On phase of the horizontal condition. A longer

trial might demonstrate continued learning of how to wield the gyroscope across a straight trajectory.

The after-effect seen in the Off phase of both orientations suggests that the properties of the gyroscope object were to some degree comparable to either transformations of properties of the reference frame (e.g., a new viscosity, as in Shadmehr & Mussa-Ivaldi, 1994) or as seen in adaptation to Coriolis forces (Cohn, DiZio, & Lackner, 2000; Lackner & DiZio, 1994). Alternatively, a transformation of the relationship between sensory information and orientation of the perceptual information as in prism adaptation shows learning aftereffects (Redding, Rossetti, & Wallace, 2005). Since such aftereffects were not seen in the control condition that used the added mass, this suggests that gyroscopes are better thought of as transformations that concern the object's reference frame to some degree rather than transformations of the object's persisting properties.

## Chapter 7: Conclusions

### Summary of findings

The reported experiments provide a glimpse into how the haptic perceptual system deals with gyroscopic forces both in isolation (Experiments 1 and 2) and in conjunction with visual information (Experiments 3 and 4). While perceivable features of gyroscopes are often explored in educational settings for learning mechanics, or for entertainment as toys, there have been virtually no formal studies of haptic perceptual judgments of gyroscope object properties. More common are studies of gyroscopes for haptic displays, in which the gyroscopic forces are used to communicate, in a representational way, information such as direction or impact.

Experiment 1 demonstrated that under specific circumstances, gyroscopic forces can be experienced as a difference in the weight of an object, and that this effect is dependent on whether the flywheel's angular momentum works to supplement or negate the torque that gravity induces on the end of the object, rather than the object's resistance to rotation generally. This is evident in the fact that the effect was only found in the unidirectional wielding mode. In the bidirectional mode, resistance to rotation was the same, but the very forces that supplemented gravity's torque in the forward wielding motion negated it when the motion was reversed. Participants' judgments were unaffected by the different force field contributed throughout the bidirectional wielding motion. We surmise, therefore, that observations that gyroscopes feel "heavier" or "lighter" are due to their reactive torques in the gravity dimension—for example, as perceivers "push against themselves" (by trying to correct the gyroscope's redirection of the perceiver's own imposed torque vectors)—rather than an intrinsic resistance to rotation (cf.

Rood, 1945). If spinning gyroscopes possessed such a resistance, the objects in Experiment 1 would have felt heavier in the bidirectional wielding mode as well as the unidirectional one.

Experiment 2 investigated whether the forgoing effects were linked to judgments of object suitability for certain tasks. While suitability ratings failed to distinguish a task that should maximize gyroscopic reactive forces (hitting) from a task that should minimize them (poking), these ratings were nonetheless generally consistent with heaviness judgments. In particular, as spin increased, ratings of heaviness increased and ratings of suitability decreased. Moreover, wielding times while object suitability was being considered increased with spin velocity, indicating an extended period of time in which participants explored the task-relevance of gyroscopic forces.

Experiment 3 required participants to displace a target by actually hitting or poking it with a gyroscope object. Successful performance was not affected by spin velocity. However, there is some evidence that participants experienced the hitting task as more difficult when the gyroscope was spinning. This may be because it required them to attune to new object properties in order to succeed.

In Experiment 4, participants performed a task that offered a more fine-grained analysis of performance than the affordance-based task. They used the gyroscope object fitted with a pointer in order to track a moving target. Gyroscopic reactive forces pushed the tip of the pointer off a straight-line trajectory, requiring participants to retune to a novel force field. The effect was more pronounced when the tracking was conducted in a vertical orientation, probably due to the reactive forces occurring in a dimension that is orthogonal to stabilization against gravity. After the gyroscopic forces were removed, participants underwent a re-tuning process similar to that

seen in prism adaptation. This process was not seen in the control condition which added a 50 g weight instead of gyroscopic forces.

Together, these findings could be summarized as reinforcing the haptic perception perspective that links heaviness perception with movability. However, the task-specificity of the effects was subtle or absent in these experimental paradigms, especially compared with the literature on perception of persisting object properties. They additionally identify gyroscopic forces in wielding as more properly understood as a means of redirecting wielding force or velocity vectors rather than amplifying or diminishing them as occurs with changing an object's mass distribution.

### **Limitations**

All four experiments assumed that vibration was negligible. While the gyroscope assemblies in this experiment used brushless DC motors which produce minimal vibration, the vibration variable was not controlled for. A practical way to characterize and reproduce the patterns of vibration that arose from the gyroscopes, without also producing the gyroscopic forces, was not apparent. However, future research that aims to control for the effects of minimal vibration may produce a solution.

### **Significance**

These four experiments offer an entry point to a new area of research on the perception-action implications of forces generated by objects. The mechanics of gyroscopes have been studied for centuries and are well established. The psychophysical implications of many mechanical forces for the haptics and for multimodal perception, while newer, are also well established. To date, however, there is very little understanding of how the haptic perceptual

system deals with mechanical forces that are more dynamically tied to moment-to-moment changes in the object's orientation. If similar processes support motor learning in distorted force fields as has been shown in prism experiments, Experiment 4 will have demonstrated the possibility for gyroscopes to serve as rehabilitative devices for patients showing spatial neglect (Newport & Schenk, 2012).

Knowing how  $L$  affects perception and action would allow an extension of the applications of so-called haptic displays that are gyroscope-based. Currently, these devices have been limited to signifying events by using discrete “kicks” of torque to a user (Murer, Maurer, Huber, Aslan, & Tscheligi, 2015; Winfree, Gewirtz, Mather, Fiene, & Kuchenbecker, 2009), or by communicating two-dimensional directional information to allow a user to consciously update their strategy of navigation through a space (Amemiya & Gomi, 2013). The experiments outlined here offer the possibility of using similar devices to simulate object properties.

In addition to sensory aids, some rehabilitation research is aimed at producing a postural aid using control moment gyroscopes (CMG). While these devices offer some promise, one potential limitation is rehabilitative patients' abilities to stand and walk under the new force field instantiated by these devices.

### **Future directions**

These experiments serve as broad overview of the consequences of the angular momentum produced by gyroscopes ( $L$ ). They demonstrate how tool movement and ease of use are affected by high ratios of angular momentum relative to tool movability features (i.e., mass, ellipsoid volume, ellipsoid symmetry). As such, each demonstrates areas in which additional study is needed to understand the implications of  $L$ .



In Experiment 1, it was shown that under special, controlled circumstances angular momentum can change perception of object weight. The subsequent experiments demonstrated that angular momentum is better understood as a transformation at a more global level. Careful gimbaled control of a mounted gyroscope (e.g., Winfree et al., 2009) or an array of gyroscopes (e.g., Walker et al., 2011) might allow for a continuous directing of reactive forces in the direction of gravity and contrary to the direction of reorienting forces. It is possible that this would simulate the weight and inertia of an object that is heavier, longer, wider, and so on, across all wielding modes (Goslin, 2017).

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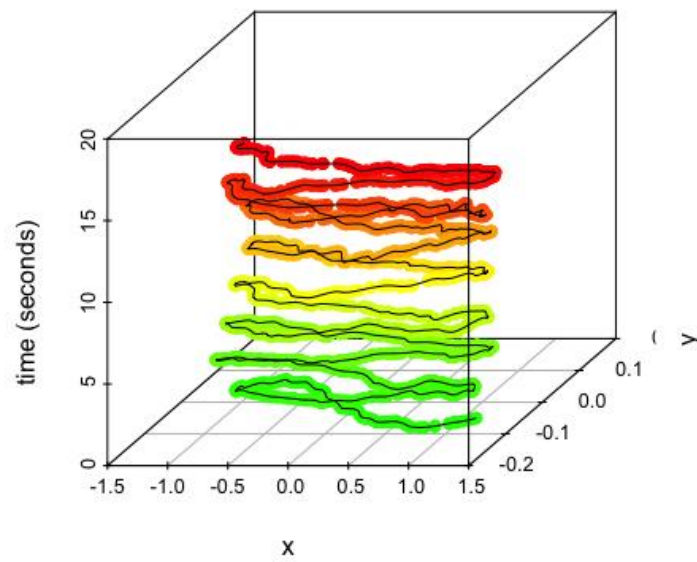
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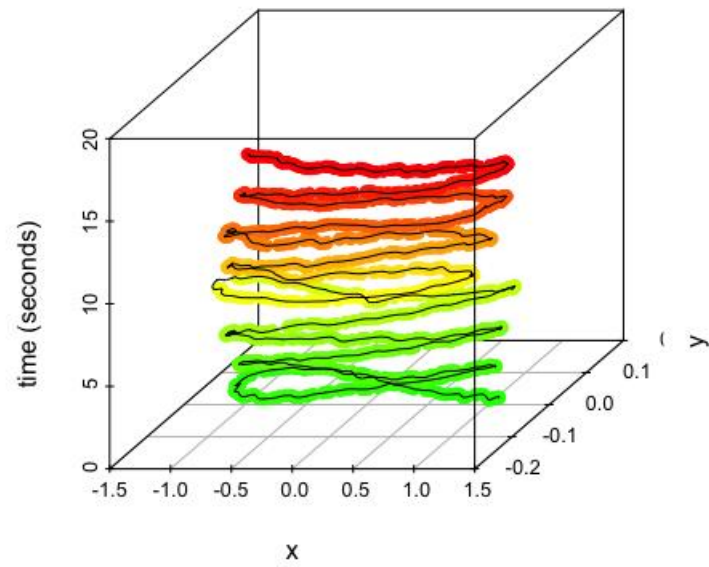
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## Appendix

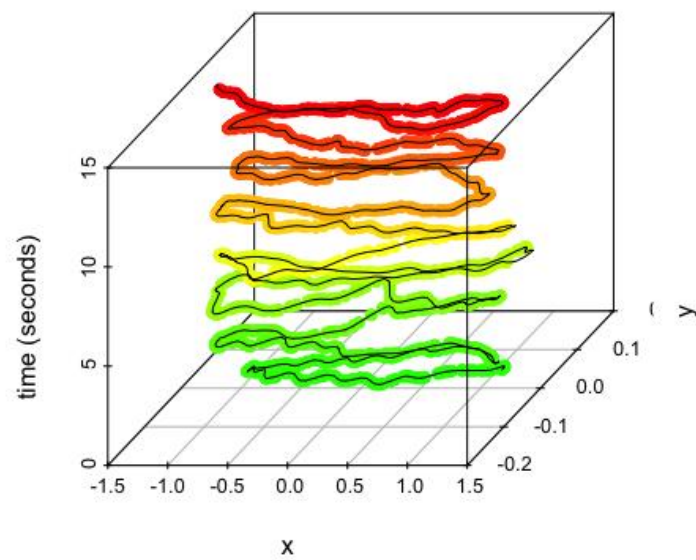
### Additional trajectory visualizations



Individual trajectory corresponds to Figures 6.2 (A) and 6.3 (A).

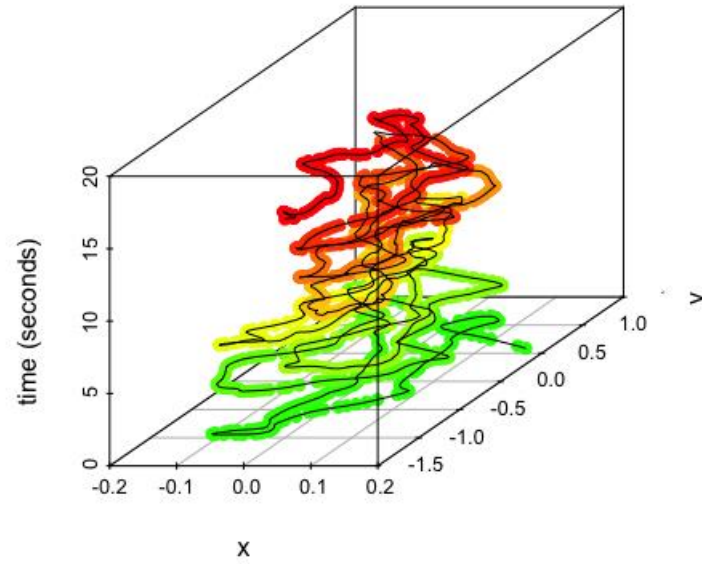


Individual trajectory corresponds to Figures 6.2 (B) and 6.3 (B).

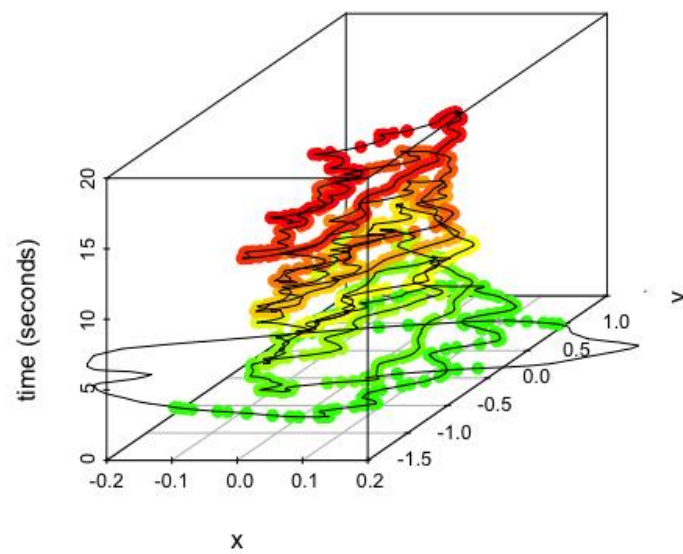


Individual trajectory corresponds to Figures 6.2 (C) and 6.3 (C).

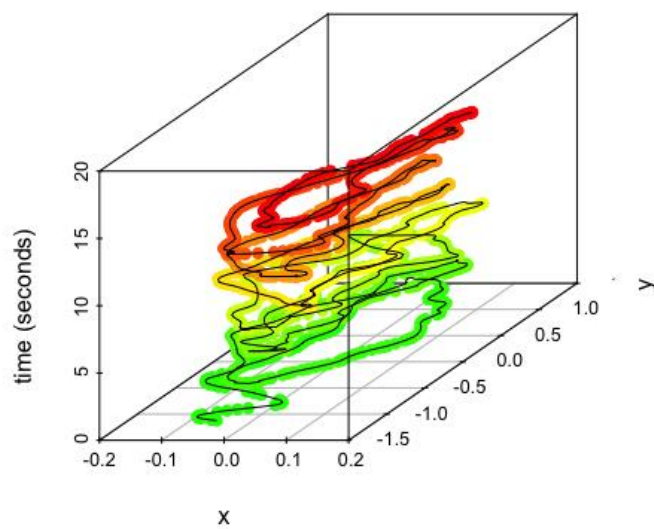




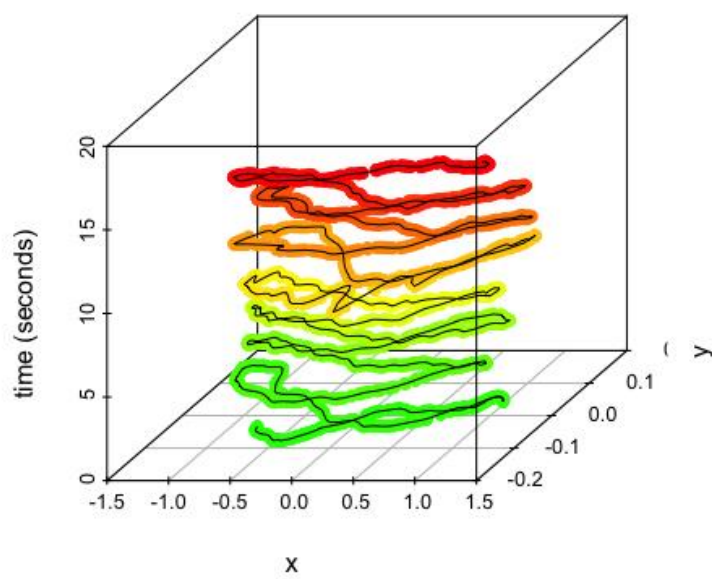
Individual trajectory corresponds to Figures 6.2 (D) and 6.3 (D).



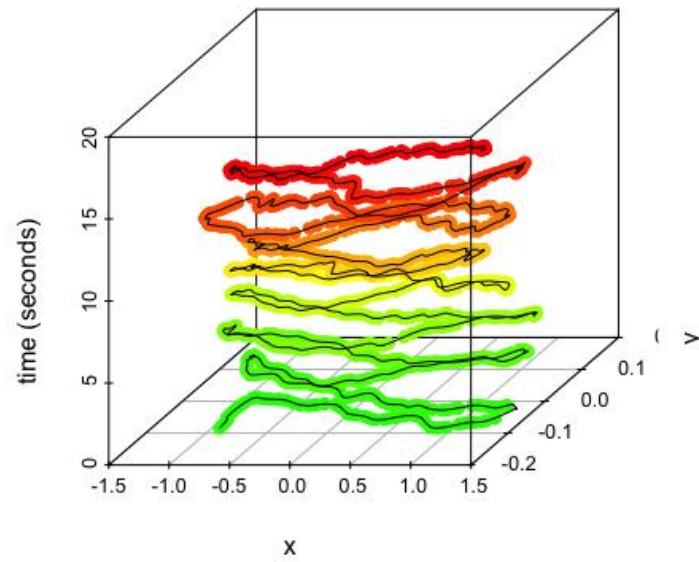
Individual trajectory corresponds to Figures 6.2 (E) and 6.3 (E).



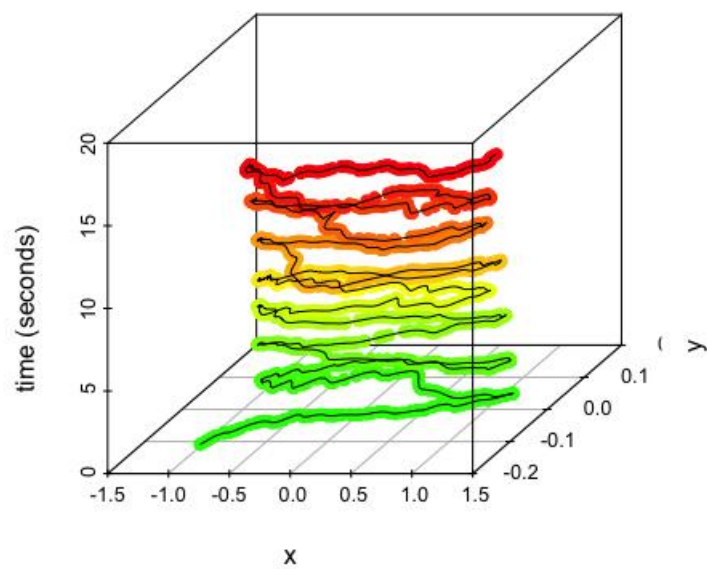
Individual trajectory corresponds to Figures 6.2 (F) and 6.3 (F).



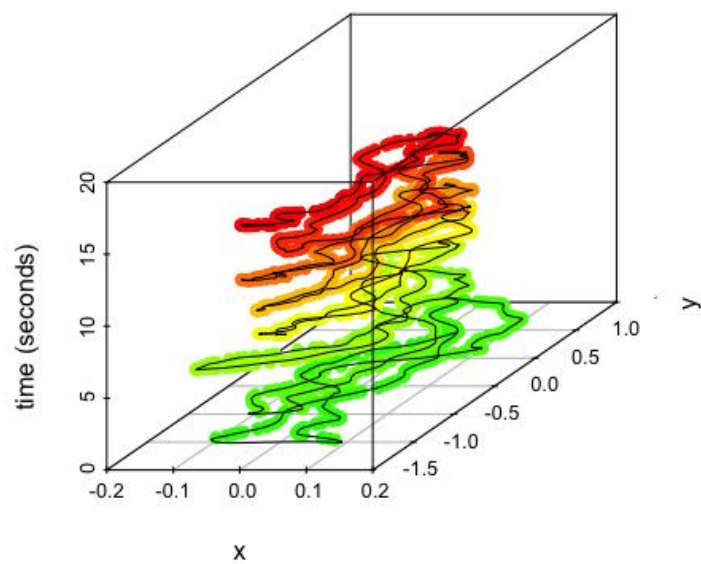
Individual trajectory corresponds to Figures 6.3 (A) and 6.4 (A).



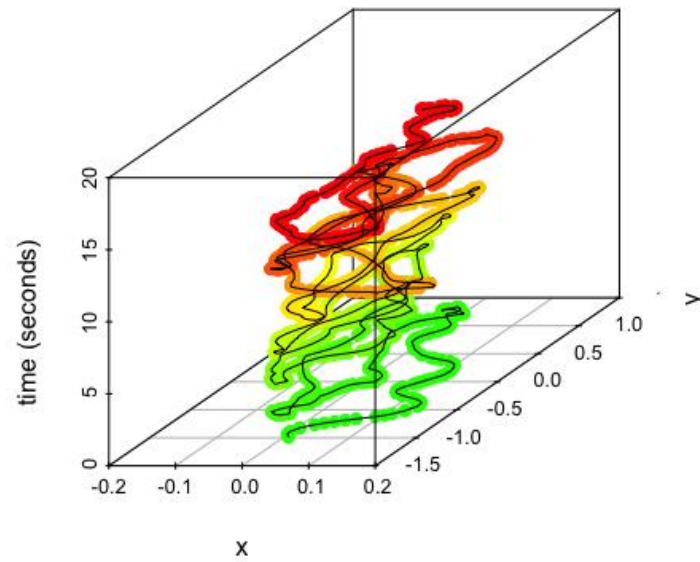
Individual trajectory corresponds to Figures 6.4 (B) and 6.5 (B).



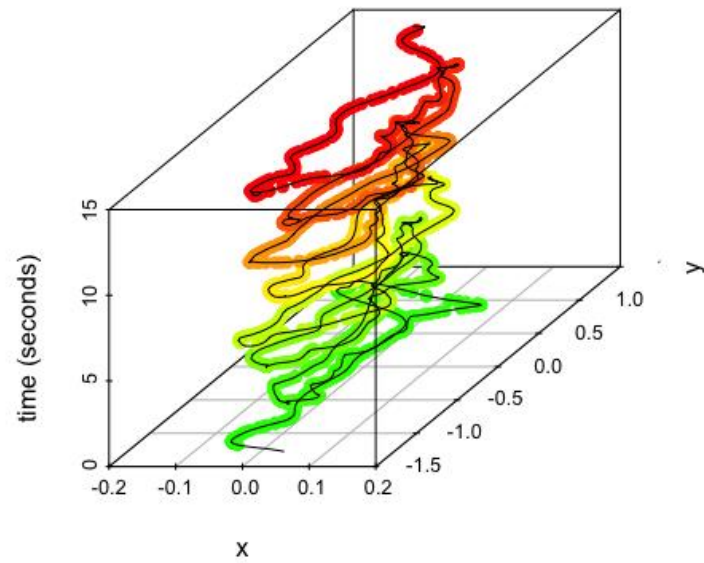
Individual trajectory corresponds to Figure 6.4 (C) and 6.5 (C).



Individual trajectory corresponds to Figure 6.4 (D) and 6.5 (D).



Individual trajectory corresponds to Figures 6.4 (E) and 6.5 (E).



Individual trajectory corresponds to Figures 6.4 (F) and 6.4 (F).